Infrastructure Quality and Imperfect Information: Evidence from Piped Water in Manila

William Violette*

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Abstract

Public utilities often need to make large investments in infrastructure quality without knowing exactly how much they will benefit consumers. Using data from a water utility in Manila, this paper estimates the effect of large-scale pipe replacements on consumer surplus both directly through increased water consumption and indirectly through lower spending on private water pumps. Detailed cost data allow for evaluating counterfactual pipe replacement policies. Minimizing engineering costs and/or maintaining strict quality standards lead to more infrequent pipe replacements, but small welfare losses relative to a full-information, optimal benchmark.

Keywords: credit constraints; consumption smoothing; water utilities.
JEL Codes: O13; E21; L95.

*Federal Trade Commission, Washington, DC. E-mail: william.j.violette@gmail.com Any opinions and conclusions expressed herein are those of the author and do not necessarily represent the views of the Federal Trade Commission or its Commissioners.

1. Introduction

To ensure service quality, public utilities often require large upfront investments such as replacing water pipes, building power generators, or expanding sewage treatment plants. The social benefits of these investments are difficult to measure because investments are infrequent, it can be challenging to precisely locate affected consumers, benefits may be external to consumer demand, and public utilities are often natural monopolies, which means that consumers cannot turn to other providers for better service quality (Spence [1975]). Without knowing these social benefits, public utilities instead base their investments on meeting service quality benchmarks and/or minimizing engineering cost calculations. Alternatively, public utility regulators may allow private companies to determine and profit from quality investments if companies are better able to measure the benefits and costs of investments. It remains an empirical question which regulatory policies best ensure socially efficient levels of infrastructure quality.

Quality regulation may have particularly large welfare consequences in developing cities where aging infrastructure and underinvestment contribute to persistently low levels of service quality. For example, over 20% of the piped water supplied in developing cities leaks from pipes before reaching consumers, resulting in low water pressure and intrusion of contaminants (Liemberger et al. [2006]). Longterm quality deficits have led households to invest in private substitutes for service quality. In Mexico City, 45% of households use rooftop storage tanks to deal with intermittent water supply (Baisa et al. [2010]) while households in urban India turn to a combination of private water tanks, pumps, and/or tube wells (McKenzie and Ray [2009]). While difficult to measure, spending on quality substitutes may be an important part of the welfare costs of low service quality.

This paper estimates the effect of water pipe replacements on consumer welfare in Manila, Philippines and then evaluates alternative pipe replacement policies. Like many developing cities, Manila initially suffered from low levels of quality investment by the public utility, which was privatized through a public-private parternship in 1997 (Dumol [2000]). Unlike in many developing cities, the public-private partnership launched a massive infrastructure upgrading program around 2008, which replaced at least 50% of the existing pipes by 2015. This paper analyzes billing and location records from 1.5 million water connections over this period as well as cost, pipe location, and survey data. Analyzing the impacts of these investments may provide useful lessons for other developing cities weighing similar programs.

The empirical strategy leverages the staggered roll-out of pipe replacements to identify its effects on household water consumption and electric booster pump use — a common substitute for low water pressure. The estimation strategy recovers the causal effect of replacements from pre/post changes in outcomes compared to changes in areas without replacements under the assumption that areas would have evolved similarly in the absence of replacements. This assumption is supported by the fact that engineers organized the pipe replacement program to meet hydrological constraints, which were unlikely to have been related to trends in local water demand.

Translating consumption changes into consumer surplus also requires estimating the price elasticity of demand. The empirical strategy analyzes novel price variation where some households are suddenly switched to 22% higher prices at different times. These switches occur when the water company notices any business activity at households' residences, which usually entails small, roadside food stands. This event-study approach complements the largely cross-sectional and time-series approaches to estimating price elasticities in the literature.[1]

Results indicate that pipe replacements have large effects on consumer welfare driven in particular by lower spending on quality substitutes. Pipe replacements are associated with a 10% increase in household water consumption and a 30 percentage point decline in booster pump use. Guided by a simple model of household water demand, these estimates suggest economically large increases in monthly consumer surplus on the order of 175 PhP or 35% of an average household water bill. Consumer utility from greater consumption and from savings on booster pumps both contribute roughly equally to the total increase in consumer surplus, highlighting the importance of private quality substitutes in evaluating infrastructure projects. Gains in consumer surplus also appear concentrated among lower socioeconomic status households.

The paper calculates the longterm welfare consequences of replacing pipes more or less frequently in different areas of the city. To calculate longterm welfare, the paper assumes that pipes deteriorate linearly over time and leverages how the observed pipe replacements effectively reset the age of the pipes from 25 years old to zero. Therefore, the estimated effects of pipe replacements on revenue, leakage costs, and consumer surplus summarize how welfare evolves over time. Estimates are conducted separately for 11 different areas of the city to simulate the spatially targeted nature of infrastructure investments.

The paper then compares welfare and pipe replacement frequencies under imper-

[1] See Szabó [2015] and McRae [2015] as well as Olmstead [2009] for a review.

fect information to those under a full-information benchmark holding fixed all other aspects of water provision. In the first case, the government regulator only observes the age of the pipes and chooses to replace pipes every 25 years, which matches the observed experience in Manila. By replacing pipes much less frequently, this policy lowers monthly welfare by around 20% of an average water bill compared to the full-information benchmark. This result suggests that Manila would have experienced substantial welfare gains by replacing its pipes sooner.

In the second case, the regulator observes the water pressure reaching consumers and sets a minimum pressure threshold, replacing pipes when pressure falls below this threshold. While the pressure threshold outperforms 25-year replacements, welfare is very sensitive to the exact threshold levels. The third case allows the regulator to observe and minimize pipe replacement and leakage costs, further improving welfare by replacing pipes more frequently on average. However, monthly welfare still lags behind the full-information benchmark by an amount equal to 6% of an average water bill.

The last case allows a regulated, private firm to schedule pipe replacements in order to maximize profits (ie. revenues minus costs) under the assumption that the firm is able to perfectly and freely observe demand and costs. Since prices in Manila are set above marginal costs, extra consumption generated by pipe replacements would give the firm an additional incentive to replace pipes quickly. This context emulates "price-cap" regulation where the regulator sets a maximum price to cover operating costs and the firm is able to profit from additional investments.[2] Profit maximization results in the next most frequent pipe replacements aside from the full-information benchmark. As a result, monthly welfare lags behind the full-information benchmark by an amount equal to only 2% of an average water bill. Consumer welfare is only slightly smaller than total welfare because high pipe replacement costs limit any potential profits earned by the firm.

This paper builds on a long literature on public utility regulation in industrial organization. While previous research, pioneered by Laffont and Tirole [1993], largely focuses on information asymmetries between firms and regulators (McRae [2015], Lim and Yurukoglu [2018]), this paper examines the case where both the regulator and the firm have imperfect information, which may be especially relevant to infrastructure quality. This paper also provides an empirical examination of the regulatory challenges inherent in measuring and regulating quality outlined by Spence [1975].

[2]See Joskow [2007].

This paper also contributes to a recent development literature studying the impacts of improved public utility service quality. Recent research has mainly focused on the impact of public utilities on health (Bhalotra et al. [2017], Kosec [2014], Ashraf et al. [2017]), education (Zhang and Xu [2016]), and productivity (Allcott et al. [2016], Hardy and McCasland [2019]). This paper measures the direct consumer surplus from improved water service quality in a similar way to how McRae [2015] recovers demand for continuous electricity service. Like Baisa et al. [2010], this paper also studies the welfare implications of spending on private substitutes to water service quality.

The paper proceeds with a discussion of the context in Manila and the datasets in Section 2. Section 3 provides descriptive statistics on water use in Manila. Section 4 develops a simple model of water demand and Section 5 outlines the empirical strategy to estimate the model. Section 6 discusses the results. Section 7 incorporates the results into counterfactual policy simulations and Section 8 concludes.

PUT FOOTNOTES IN TO EXPLAIN THE AMOUNTS!!

Conclusion should discuss REGULATION THEORY!!

Key notes to fill in later: - Ignore externalities of booster pumps - No quantity margin because of splitting of taps and because census data indicates really high coverage - Reweight by household number - Also measure by closest pipe for robustness - Measure cost savings from less NRW! – flag potential spillovers in NRW that we're missing... - could do non-linear pricing robustness check

2. Data and Setting

As a pioneer in water infrastructure investments among developing cities, Manila provides a useful context to study the welfare effects of these types of pipe replacements. Before 1997, a single government utility provided water to Manila resulting in low levels of service quality (Dumol [2000]). In 1997, Manila awarded private concession contracts to two private companies to take over for the public utility. Each company was assigned to provide water to their assigned halves of Metro Manila. The two companies are regulated by a government agency who sets the water tariff in order to ensure that the companies are able to cover their costs while earning a fair rate of return on their assets. The regulator also reserves the right to disallow costs that it views as inessential to water provision. Privatization led to large improvements in water access such that by 2015, piped water usage was almost universal.[3] This paper analyzes data provided by one of the companies.

In 2008 in agreement with the government regulator, the water company started aggressively replacing the decaying pipe infrastructure that it inherited from the public utility. Guided by hydrological concerns, the company separated the service area into smaller sections and replaced most pipes in each section on a sequential basis. The existing pipes were mostly installed between 1980 and 1990 with an average year of 1986.[4] Between 2008 and 2015, the water company replaced over 57% of its nearly 6,000 km of pipes.

To measure the effect of pipe replacements, the company provided a map of their water pipes including the installation year for each pipe as well as water billing records for their 1.5 million water connections from January, 2008 to June, 2015.[5] To measure each water connection's exposure to pipe replacement projects, connections are first located within "small areas" — the smallest geographic designations used by the company with 2,976 total areas each containing around 270 connections. Next, since projects often replace many pipes in the same place at the same time, each small area is assigned a "pipe replacement year" according to the year when at least 80% of the total length of tertiary pipes were installed within that small area. 576 small areas are observed before and after their "pipe replacement year." Tertiary pipes act as local feeders transporting water from large primary and secondary pipes directly to households. Therefore, tertiary pipe replacements likely affect service quality within local areas while primary and secondary pipe replacements may have diffuse impacts throughout the pipe network. By excluding primary and secondary pipe replacements, this approach limits the potential for spillover effects of pipe replacements onto neighboring areas at the cost of potentially underestimating the total welfare gains from these projects.

Billing records measure monthly water prices and usage for each water connection, which may serve multiple households. In order to link connection-level consumption to household welfare, billing records for each connection are merged to a survey of residential water connections conducted by an independent evaluator to monitor compliance with the water utility's service obligations.[6] This connection survey records demographics for the household that owns the connection as well as the number of

[3] Less than 2% of households report using well water, water peddlers, or other alternative water sources for cooking according to the 2015 Census of Population and Housing.
[4] DISCUSS APPENDIX ABOUT PIPE AGE.
[5] Data is missing for the month of June, 2014.
[6] The billing records also cover commercial and industrial accounts.

other households and people that also use the connection. The survey also includes household demographics for the connection owner, different measures of water service quality, as well as household investments in booster pumps, water filters, and water storage tanks.

The main outcome of interest is household-level water usage, which is calculated by dividing total connection usage by the number of households sharing the connection. Outlier months with over 200 m3 of consumption are excluded from the analysis. All empirical results are weighted at the household-level to ensure that results are representative of the population of households.

The survey randomly interviewed water connection owners covering 15,000 connections in 2008, 24,000 connections in 2010, and 23,000 connections in 2012. Because a similar sampling design was followed across survey rounds, 13% of connections were interviewed in two years, and 1.4% of connections were interviewed in three years while remaining connections were interviewed in only one year. The connection survey is merged to the billing records by the connection id number and the interview month. For billing-record months without corresponding interviews, survey responses are interpolated with responses from the most recent interview.

Since households face an increasing block water tariff, the average water price faced by households is calculated as the average amount paid per cubic meter of water usage for each calendar month and tariff category after dropping outlier values below 5 PhP/m3 and above 100 PhP/m3.[7] Outliers are often due to billing credits/errors. To measure savings from pipe replacements, the water company also provided records of project costs as well as the quantity of water supplied, which often exceeds the quantity of water billed. These attributes are measured according to "district metering areas," which are around three times larger than small areas and are delineated based on hydrological considerations in order to monitor water loss.

3. Descriptives

Descriptive evidence indicates that fixing pipes improves water pressure, quality, and reliability, which may each affect consumer welfare. Table 1 tracks water service improvements by comparing average household survey responses before and after pipe

[7]Households either face a standard tariff or a high-price tariff depending on whether they are observed with business activities at their residence. See Section 3 for more discussion.

replacement for areas that are observed both before and after.[8] The share of households reporting strong water pressure during peak evening usage from 6pm to 12am increases from 25% to 58% after pipe replacements. Likewise, the share reporting no pressure over the same interval decreases from 29% to 4%. Water interruptions decline slightly from 2.28 to 1.93 in the last three months, which is consistent with the water company facing periodic droughts. Water quality shows large improvements with the share of respondents reporting discolored, unusual tasting, or contaminated water dropping by at least 5 percentage points for each measure.

Households often invest in products and behaviors to compensate for low piped water service quality. These investments help reveal which aspects of piped water service are most valuable to consumers as well as most affected by pipe replacement.

Large investments in booster pumps suggest that households strongly value water pressure and reliability. Booster pumps are both expensive to purchase and operate. In Manila, booster pumps range in price from 1,200 to 15,000 PhP, which represents a large expense given average monthly household incomes of 26,023 PhP.[9] The average booster pump uses a 0.9 horsepower engine, which generates monthly costs of around 486 PhP at prevailing energy prices.[10] Before pipe replacement, 40% of households invest in booster pumps that increase water pressure. After pipe replacement, the share of households using booster pumps drops to 15%. This finding is consistent with booster pumps providing an important substitute to pressure from new water pipes.

Small investments in water filters combined with frequent purchases of filtered water both before and as well as after pipe replacement indicate that households may derive fewer benefits from improvements in piped water quality. Only 12% of households use water filters both before and after pipe replacements. Low filter usage may stem from the fact that less than half of households report drinking from the tap while over 70% of households report purchasing filtered water from local water-refilling stations. These behaviors remain constant after pipe replacements. Taken together, these findings indicate that water quality improvements from pipe replacements may not be

[8]Areas that may have experienced pipe replacements before the start of the sample are included in the "All" category.

[9]Figures come from scraping results from the first page of searching "booster pumps" on the popular online marketplace in Manila, `https://www.lazada.com.ph/`, yielding 24 entries with horsepower listed. Average monthly household income is computed for Metro Manila using the 2015 Family Income and Expenditure Survey.

[10]A 1 horsepower engine uses around 0.786 Kw per hour. Table 1 indicates that households use their booster pumps for 2.6 hrs per day, which implies around 78 hours per month. In 2012, tariffs for the electricity utility in Manila averaged around 8.8 PhP per KwH.

primary drivers of changes in household welfare.

Households cope with unreliable water supply by investing in water storage tanks. Before pipe replacement, 43% of households report using water storage tanks. This percentage only drops to 36% following pipe replacement, which is consistent with households continuing to report frequent water outages even after pipe replacement. While households seems to value reliable service, small changes in storage tank use suggest that reliability improvements are unlikely to account for a large share of the welfare gains from pipe replacements.

Increases in water pressure from pipe replacements may lead households to increase their monthly water consumption. Rapid water flow allows households to complete a greater number of water-using activities like cleaning and bathing in the same amount of time. Greater water pressure may also allow households to engage in new activities that require minimum pressure levels such as showering. Cleaner water may induce households to use more tap water for cooking and cleaning. Figure 1 plots average monthly water usage per household in the 4 years before and 6 after pipe replacement. Usage increases from an average of 18.5 m3 before pipe replacement to 21.1 m3 after pipe replacement, which represents an 14% increase. The increase in usage occurs abruptly at the year of pipe replacement and remains at roughly the same level in the following 6 years. This sustained increase in consumption suggests that pipe replacements may provide long-term impacts on household welfare.

The absence of strong pre-trends in usage suggests that replacement projects are not targeted to areas with particular trends in local water demand. Instead, this pattern is consistent with the company's stated goal of sequentially replacing old pipes according to hydrological specifications. Table 1 further supports this theory by indicating few demographic differences between households that receive pipe replacement projects (columns (1) and (2)) and all households (column (3)). Also, demographic characteristics appear relatively similar before and after pipe replacement, which suggests that pipe replacements were not coupled with other policies that may have also affected demand for water.

Mapping these increases in consumption into household welfare requires measuring how households trade off water usage and price. Prices are determined by the government regulator who imposes an increasing tariff schedule according to monthly usage, which is standard among public utilities (Hoque and Wichelns [2013]). Despite steep increases in marginal price at specific levels of usage, households do not appear to be sensitive to these price changes because households are not observed adjusting

Figure 1. Average Water Usage per Household with Years to Pipe Replacement

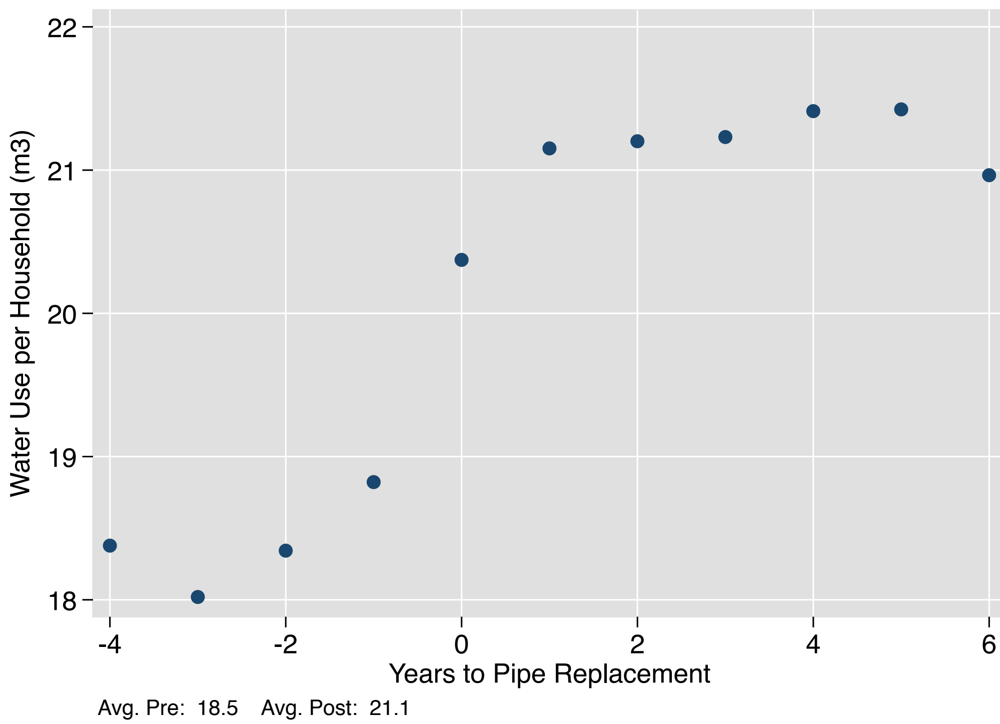


Table 1. Average Survey Responses Before and After Pipe Replacement

	Before	After	All
Piped Water Service Quality			
Water has strong pressure (6pm-12am)†	0.25	0.58	0.48
Water has no pressure (6pm-12am)†	0.29	0.04	0.09
Water interruptions in last 3 months	2.28	1.93	2.13
Water has foreign bodies	0.24	0.04	0.12
Water is discolored	0.08	0.03	0.04
Water has unusual taste/smell	0.12	0.03	0.05
Household Service Quality Investments			
Has booster pump	0.39	0.11	0.16
Hours booster pump is used per day	2.79	2.57	2.51
Has water storage tank	0.41	0.34	0.39
Has water filter	0.11	0.10	0.10
Purchases filtered water	0.69	0.74	0.69
Purchases from a deepwell	0.05	0.02	0.03
Spending on non-piped water (PhP)	90.94	89.25	87.18
Drinks from the tap	0.49	0.45	0.52
Demographics			
Household size	4.91	4.94	4.96
Employed members	1.56	1.38	1.48
Respondent has high-skilled employment	0.11	0.08	0.09
Lives in duplex	0.25	0.29	0.26
Lives in single house	0.48	0.45	0.51
Number of other households sharing tap	0.84	0.86	0.90
Households	10,235	9,136	49,319

† when not using booster pump. Bill, Unpaid Balance, Payment, and Income are in PhP. Measures exclude months where households remain disconnected through the end of the sample period. Billing data include households for household-month observations. Income data include households for household-month observations. 45 PhP = 1 USD

their consumption strategically to avoid higher prices.[11] The regulator also increases

[11] Appendix Figure 4 includes the average tariff schedule for users facing low and high prices. Appendix Figure 5 includes a histogram of usage per connection and finds little evidence of significant bunching at the tariff kink points at 10, 20, and 40 m3.

prices gradually over time to ensure that the company continues to cover operating costs. Since households also gradually increase their average usage over this interval, it is unclear whether households are responsive to these price increases.[12]

The empirical exercise analyzes an event-study where the same households are exposed to very different price levels over time. The government regulator gives the water company discretion to assign households to a high-price tariff schedule if they have any business activity at their residence, which provides a novel source of price variation in the context of public utilities. In the vast majority of cases, the high price tariff is applied to households that operate small food stands (or "Sari-Sari" stores). For a household with average monthly usage, the high-price tariff results in an average price of 26.4 PhP/m3 while the regular tariff results in an average price of 21.5 PhP/m3.[13] The water company occasionally visits consumers and assigns consumers to the high-price tariff if business activity is observed at the residence.[14] Table 2 provides average characteristics of households that are observed with the regular price (in column (1)), that are observed with the high price (in column (2)), and that are observed increasing prices during the sample (in column (3)). While the 724 households that experience price increases use more water than other households, they share similar demographic characteristics, which suggests that they may also share similar price-sensitivities.

Figure 2 plots average usage and marginal prices 4 years before and after households are first switched from the regular price to the high price.[15] Before the price change, average usage increases likely due to some households using additional water for their small-businesses. The price change at month 0 is associated with a sharp drop in usage and increase in average prices that persist for at least 24 months. These patterns indicate that household water usage is sensitive to large, discrete price changes over time.

4. Model

A simple model of household water demand connects changes in water usage and investments in water booster pumps to changes in household welfare as a result of

[12] Appendix Figure 3 plots average prices and usage per household over time.

[13] Appendix 4 plots the tariff.

[14] In some cases, consumers request price decreases when they close their businesses. These price-decrease events are not the focus of the analysis because consumers directly anticipate these events and may otherwise have adjusted their water usage accordingly.

[15] In very few cases, households are later switched back to the regular price, and then switched again to the high price.

Figure 2. Water Usage and Price Changes

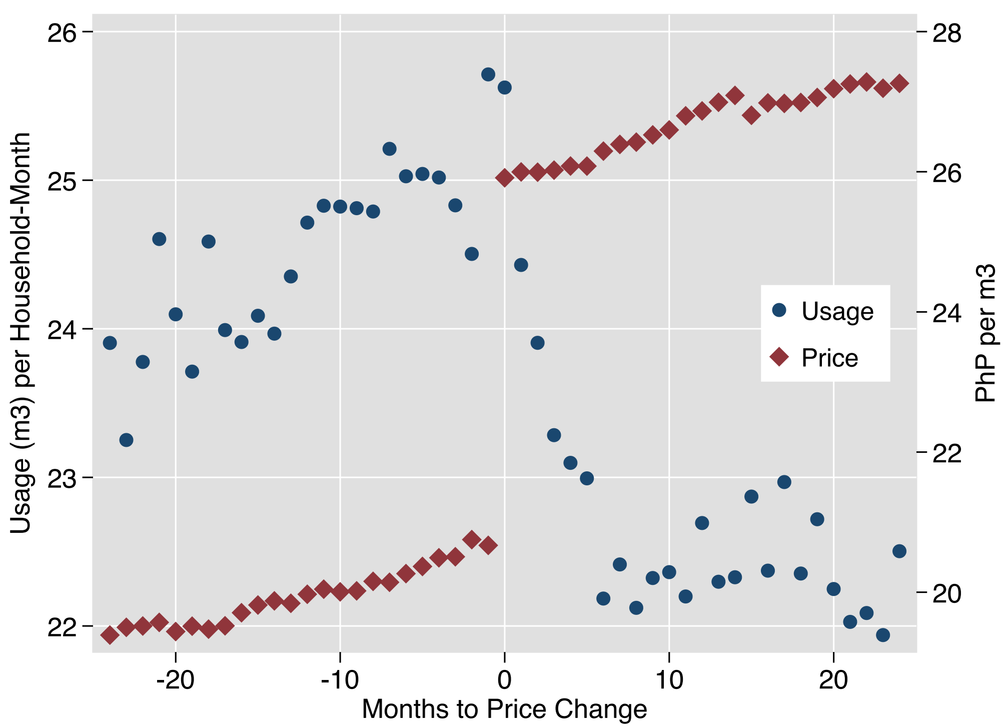


Table 2. Average Household Characteristics by Prices Charged

	Always Reg. Price	Always High Price	Change Reg. to High Price
Usage per household (m3)	19.95	20.17	23.42
Household size	4.98	4.74	4.99
Employed members	1.49	1.42	1.39
Respondent has high-skill employment	0.09	0.06	0.05
Lives in a duplex	0.26	0.26	0.27
Lives in a single house	0.50	0.59	0.54
Other households sharing tap	0.90	0.93	0.96
Households	43,901	4,694	724

Reg. refers to regular price.
Pressure is 6 to midnight! Bill, Unpaid Balance, Payment, and Income are in PhP. Measures exclude months where households remain disconnected through the end of the sample period. Billing data include households for household-month observations. Income data include households for household-month observations. 45 PhP = 1 USD

pipe replacements. In this model, households choose their monthly water usage as well as whether to use a booster pump to boost their water pressure.

Each month, household utility takes the following form

$$U = \frac{1}{\alpha}\left[\, Q(B,R)\,w - \frac{1}{2}(w-\gamma)^2 \,\right] + x \tag{1}$$

where w is water usage and x represents a bundle of all other goods consumed by the household. Water service quality given by the function, $Q(B,R)$, depends on booster pump use where B equals 1 if the household chooses to use a booster pump (and zero otherwise) and as well as pipe replacements where R equals 1 after pipe replacement (and zero otherwise). $Q(B,R)$ is assumed to be differentiable in R. Water service quality enters multiplicatively with water usage, which nests the assumption that each unit of water usage is affected equally and positively by water service quality. This assumption also excludes the possibility that improved water service quality affects household utility in ways that are not directly proportional to household water usage such as by increasing housing values. In this case, the approach would underestimate the welfare benefits of improved service quality. α reflects price sensitivity, and γ reflects the satiation amount of water usage. This approach assumes that preferences for water are quasi-linear, which implies that water usage does not depend on household income [

Footnote to heterogeneity table].

Households maximize utility subject to the following budget constraint

$$pw + x + BF = Y \tag{2}$$

where p is the average price of water while the price of all other goods, x, is normalized to 1. This approach includes the simplifying assumption that households respond to a single, average water price p despite facing marginal prices that increase with monthly usage. This assumption is consistent with descriptive evidence that households appear unresponsive to marginal prices.[16] F is total cost of renting and using a booster pump each month. This approach assumes that Manila has a competitive market for renting and selling booster pumps that is unaffected by improvements in piped water service quality.[17] Y is monthly household income.

Maximizing household utility in equation (1) subject to the budget constraint in equation (2) for a given choice of booster pump usage, B, yields the following expression for monthly water demand

$$w(B) = \gamma - \alpha p + Q(B,R) \tag{3}$$

Water demand depends linearly on the satiation preference, γ, price, and service quality.

Given optimal water demand, the indirect utility function at a given booster pump choice, B, is given by

$$V(B) = \frac{\alpha p^2}{2} - \gamma p + \frac{Q(B,R)^2}{2\alpha} - pQ(B,R) + \frac{\gamma Q(B,R)}{\alpha} + y - BF \tag{4}$$

The derivative of V with respect to pipe replacements, R, reflects the change in consumer welfare associated with pipe replacements. This derivative takes the following form after substituting terms for $w(B)$

$$\frac{dV(B)}{dR} = \frac{w(B)}{\alpha}\frac{dQ}{dR} - F\frac{dB}{dR} \tag{5}$$

This expression summarizes the consumer welfare effects of pipe replacements in terms

[16] Appendix Figure 5 includes a histogram of usage per connection and finds little evidence of significant bunching at the tariff kink points at 10, 20, and 40 m3.

[17] This assumption is consistent with local service quality improvements and a city-wide market for booster pumps.

of (1) the marginal effect on service quality weighted by water usage and price sensitivity as well as (2) the marginal effect on booster pump usage weighted by the cost of booster pumps. This approach assumes that welfare effects are proportional to usage, w^*, implying that service quality improvements affect all units of water usage. Welfare effects are decreasing in price sensitivity, α, which captures the intuition that households with many substitute water sources (ie. high α) may benefit less from improvements in service quality. According to this approach, welfare changes do not require measuring fixed preferences, γ, separately from levels of service quality, $Q(B, R)$. Therefore, this approach is robust to different patterns of selection into booster pump use based on different levels of service quality or fixed preferences for water usage.

5. Empirical Strategy

The empirical strategy estimates household price sensitivity as well as changes in water usage and booster pump use in response to pipe replacement projects. These estimated quantities inform the effect on consumer welfare of pipe replacement projects given by equation (5). Using an instrumental variables approach, the empirical strategy isolates price variation from connections being switched into high price tariffs. The first stage equation takes the following form

$$p_{it} = \phi_1 \text{Post Pipe}_{tl} + \phi_2 \text{Post Price}_{it} + \phi_3 \text{Pre Trend}_{it} + \phi_4 \text{ Post Trend}_{it} + \phi_t + \phi_{il} + \epsilon_{itl} \quad (6)$$

where i indexes the water connection, t indexes calendar month, and l indexes small area. p_{it} is the average price per cubic meter of monthly water use. Post Pipe_{tl} is an indicator for months during and after January of the pipe replacement year. Post Price_{it} is an indicator for months after a connection is first switched into a high-price tariff.[18] Post Price_{it} is the instrumental variable that is excluded in the second stage. To account for trends in water usage around the time of the price change, Pre Trend_{it} counts the months leading up to the first price increase and takes a value of zero otherwise. Likewise, Post Trend_{it} counts months after the first price increase and takes a value of zero otherwise. ϕ_t are calendar month fixed effects. ϕ_{il} are connection fixed effects when the second stage has water usage as an outcome. ϕ_{il} are small-area fixed effects when the second stage has booster pump use as an outcome because booster pump use is only observed in months where the connection survey was fielded.

[18] In rare instances, connections may be switched into high-price tariffs more than once during the study period. The instrumental variables design ensures that the estimation uses price variation only from the first price increase, which is more likely to be unexpected by households than later price increases.

Given predicted prices from the first stage equation, the second stage equations take the following form

$$w_{itl} = \gamma_1 \text{Post Pipe}_{tl} + \gamma_2 \hat{p}_{it} + \gamma_3 \text{Pre Trend}_{it} + \gamma_4 \text{Post Trend}_{it} + \gamma_t + \gamma_i + \varepsilon_{itl} \tag{7}$$

$$b_{itl} = \beta_1 \text{Post Pipe}_{tl} + \beta_2 \hat{p}_{it} + \beta_3 \text{Pre Trend}_{it} + \beta_4 \text{Post Trend}_{it} + \beta_t + \beta_l + \varepsilon_{itl} \tag{8}$$

where w_{itl} is water usage per household in cubic meters per month and b_{itl} is an indicator for connection booster pump usage.

The coefficients of interest for the impacts of pipe replacement are given by γ_1 and β_1 for water and booster pump use respectively. After controlling for calendar month and connection fixed effects, these coefficients are identified from differential changes in outcomes for areas that experienced pipe replacements compared to areas that did not over the same interval. These coefficients reflect the causal effect of pipe replacements under the assumption that no other factors changed at the same time that would otherwise affect the outcomes. This assumption is supported by qualitative evidence that pipe replacements are often driven by hydrological, engineering concerns rather than strategic responses to changes in local water demand or other consumer characteristics. Supporting this assumption, Figure 1 traces a sharp break in average usage at the year of pipe replacement with little evidence of strong trends before or after replacement projects.

To estimate the effects of pipe replacement change over time, additional specifications replace the terms, γ_1Post Pipe$_{tl}$ and β_1Post Pipe$_{tl}$, with the terms, $\sum_{k=0}^{K} \gamma_1^k \text{Post Pipe}_{tl}^k$ and $\sum_{k=0}^{K} \beta_1^k \text{Post Pipe}_{tl}^k$, where k indexes years after pipe replacement, Post Pipe$_{tl}^k$ is an indicator variable for each k year after pipe replacement, and coefficients, γ_1^k and β_1^k, measure the lasting effects at each k year after pipe replacement.

To estimate heterogeneity according to household characteristics, further specifications replace the terms, γ_1Post Pipe$_{tl}$ and β_1Post Pipe$_{tl}$, with the terms, $\sum_{j=1}^{J} \gamma_1^j \mathbb{1}\{D^j = 1\} \times \text{Post Pipe}_{tl}$ and $\sum_{j=1}^{J} \beta_1^j \mathbb{1}\{D^j = 1\} \times \text{Post Pipe}_{tl}$, where j indexes household characteristics, $\mathbb{1}\{D^j = 1\}$ is an indicator variable for households with characteristic, j, and coefficients, γ_1^j and β_1^j, measure the effects of pipe replacements for households with characteristic, j.

The effects of prices on outcomes are given by γ_2 and β_2 for water and booster pump use respectively where $\hat{p}_{it}$ is the predicted price from the equation (6). The effects are identified from changes just before and after connections are switched to a high-price tariff after controlling for trends leading up to and after the tariff change. The validity of this instrumental variables approach requires both that the tariff change produces a large impact on prices and that no other factors affect demand for water or booster pumps at the same time as the price change. This approach assumes that while households may increase their water usage as they start small home businesses, households are unable to anticipate the exact timing of the price change so that any changes in water usage in the months just following the price change can be attributed to the higher prices. Figure 2 traces a smooth, increasing trend leading up to the price change. Usage then drops abruptly at the same time as the price change, consistent with a surprise increase in prices.

The estimated coefficients directly inform the expression for welfare in equation (5). According to equation (3), water quality linearly affects water demand. Therefore, by capturing the effect of pipe replacements on water demand, γ_1 measures the total change in water quality from pipe replacements, $\frac{dQ}{dR}$. β_1 measures the reduced form impact of pipe replacements on booster pump usage, $\frac{dB}{dR}$.

The remaining term to be estimated in equation (5) is the price sensitivity, α. γ_2 captures the reduced form effect of prices on water usage. By taking the derivative of equation (6) with respect to price, this effect can be expressed as a function of the price sensitivity as well as the effect of price on water quality through endogenous changes in booster pump use, according to the following equation

$$\gamma_2 = \alpha + \frac{dQ}{dB}\frac{dB}{dp} \tag{9}$$

where $\frac{dQ}{dB}$ is the effect of booster pump use on water quality, which is unobserved. $\frac{dB}{dp}$ is the effect of prices on booster pump use, which is estimated by β_2. If $\frac{dB}{dp}$ is zero, then the expression reduces to $\gamma_2 = \alpha$. Although the booster pump decision is not explicitly modeled, $\frac{dB}{dp}$ may be zero or close to zero when booster pump use is primarily driven by other factors besides the price of water. For example, booster pumps may be a perfect substitute for water quality such that all households below a certain water quality level choose to use booster pumps while all households above this level do not use booster pumps. In this example, the booster pump decision is orthogonal to water prices.

6. Results

Table 3 includes the main estimates of the effects of average price and pipe replacements on water and booster pump use. The first row of Column (1) finds an average increase in household water usage of 2 m3 per month after pipe replacement. The estimate is statistically significant at the 1% level and economically large, representing a 10% increase in average household water use. The first row of Column (2) finds that pipe replacement projects are associated with a 22 percentage point average decrease in booster pump use, which is statistically significant at the 1% level. This estimate also represents an economically significant decrease given that the average level of booster pump use across the full sample is 16%.

Columns (2) and (4) provide separate effects for each year after pipe replacements. According to Column (2), the effect on water use is highest in the first two years after pipe replacement at around 2.3 m3 before declining linearly to around 2 m3 at 6 years after pipe replacement. Column (4) finds a similar declining pattern for booster pump use between one and two years after pipe replacement. Booster pump effects beyond two years are unavailable because the connection survey only covers a limited time period. Columns (2) and (4) find a relatively smaller effect in the year of construction likely because many projects were completed at some point during this year.

The declining effect over time is consistent with pipes gradually deteriorating. The linear trend in the decline matches civil engineering research documenting a roughly linear relationship between pipe failure and pipe age especially within the first 50 years after installation.[19] Extrapolating the linear trend suggests that households would return to their pre-replacement consumption levels within around 37 years. In contrast, the average age of the replaced pipes is around 25 years, which suggests that the new pipes may be more durable or subject to better maintenance than the replaced pipes.

In terms of estimating price sensitivity, the second row of column (1) provides a reduced form effect of prices on water use of 0.59, which is statistically significant at the 1% level.[20] Since the second row of column (2) finds zero effect of price on booster pump use,[21] then the reduced form effect of price on usage can be interpreted directly as household price sensitivity according to equation (9). Given an average price of 21.5 PhP/m3, this estimate implies a price elasticity of 0.64. This elasticity estimate is in the middle of the range from 0.01 to 0.98 in the developing world.[22]

These results allow for benchmarking the average effect of pipe replacements on consumer welfare over 6 years according to equation (5). Using inputs from column

[19]See Ward et al. [2017], Kleiner and Rajani [2001], and Aydogdu and Firat [2015].

[20]Appendix Table 10 indicates that the first-stage is statistically significant and the t-statistic is at least 17 across specifications.

[21]Although the price effect is identified from only the 208 connections that are surveyed after being switched into a high price tariff, the estimate is relatively precise ruling out effects above 3.7% and below -2% with 95% confidence.

[22]See Szabó [2015], Diakité et al. [2009], and Strand and Walker [2005].

(1) of Table 3, consumer surplus from improved water quality computes to around 68 PhP per household/month while consumer surplus from lower booster pump usage computes to around 107 PhP per household/month. This result suggests that both factors are similarly important in driving changes in consumer welfare.

Table 4 tests for heterogeneity in responses to pipe replacements according to household demographic characteristics. Columns (1) and (2) include results for water use and Columns (3) and (4) include results for the natural logarithm of water use plus one to account for months with zero consumption. Coefficients in Columns (3) and (4) can be interpreted approximately as percentage effects. The effects of pipe replacements on water use are stronger for households living in subdivided or freestanding houses relative to those living in apartment buildings. Apartment buildings may invest in large-scale water pumps or small water towers to ensure water flow while houses may be unable to make these large investments and are often located further from central water pipes. The effects on water use are weaker for households where the household head is employed in a high-skilled job as well as for households with more employed household members relative to other households. This finding is consistent with higher income households investing in water quality substitutes or locating in areas with better service quality. Columns (5) and (6) test for heterogeneous effects on booster pump use, finding no evidence of differential responses according to household characteristics. Overall, these results suggest that pipe replacements have positive distributional effects since water quality benefits appear to accrue more strongly for lower income households.

7. Policy Counterfactuals

This section uses the empirical estimates to simulate the welfare effects often five policies for replacing pipes. Section 7.1 discusses a simple framework and assumptions for simulating each policy. Section 7.2 outlines the empirical inputs. Section 7.3 discusses the results of the simulations.

7.1. Policy Framework

The counterfactuals focus on the role of pipe replacements by holding fixed other aspects of water utility operation and regulation. The full population of Manila is assumed to remain connected to service indefinitely. The water tariff is assumed to be determined independently of pipe replacements and to exactly cover all other costs of

Table 3. Household Water and Booster Pump Use Estimates

	(1) Water Use	(2) Water Use	(3) Booster Pump Use	(4) Booster Pump Use
After Pipe Replacement	2.01[a]		-0.22[a]	
	(0.15)		(0.02)	
3-6 yr Before Pipe Rep		0.33		-0.09[a]
		(0.21)		(0.02)
2 yr Before Pipe Rep		-0.33[b]		-0.00
		(0.14)		(0.03)
Year of Pipe Rep		1.47[a]		-0.19[a]
		(0.12)		(0.02)
1 yr After Pipe Rep		2.25[a]		-0.31[a]
		(0.15)		(0.04)
2 yr After Pipe Rep		2.24[a]		-0.28[a]
		(0.16)		(0.03)
3 yr After Pipe Rep		2.07[a]		
		(0.17)		
4 yr After Pipe Rep		2.10[a]		
		(0.20)		
5-6 yr After Pipe Rep		1.94[a]		
		(0.22)		
Avg. Price (PhP)	-0.59[a]	-0.59[a]	-0.00	0.00
	(0.10)	(0.10)	(0.01)	(0.01)
Mean	19.83	19.83	0.16	0.16
R^2	0.001	0.001	0.018	0.022
N	4,004,445	4,004,445	48,982	48,982
Connection FE	✓	✓		
Small Area FE			✓	✓
Dataset	Billing Panel	Billing Panel	Connection Survey	Connection Survey

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

Table 4. Heterogeneity in Estimates by Household Characteristics

	(1) Water Use	(2) Water Use	(3) log(Water Use + 1)	(4) log(Water Use + 1)	(5) Booster Pump Use	(6) Booster Pump Use
After	1.172[a]	1.279	0.098[a]	0.076	-0.216[a]	-0.246[b]
	(0.333)	(0.866)	(0.021)	(0.054)	(0.026)	(0.109)
Avg. Price (PhP)	-0.596[a]	-0.327	-0.022[a]	-0.002	-0.000	0.031
	(0.101)	(0.303)	(0.006)	(0.015)	(0.012)	(0.048)
After × Household Size	0.082		-0.002		-0.001	
	(0.061)		(0.004)		(0.002)	
After × Employed Household Members	-0.117		-0.010[c]		0.005	
	(0.098)		(0.006)		(0.004)	
After × High Skilled Employment	-1.317[a]		-0.070[a]		-0.009	
	(0.357)		(0.019)		(0.019)	
After × Subdivided House/Duplex	0.765[b]		0.084[a]		-0.005	
	(0.307)		(0.021)		(0.015)	
After × Freestanding House	1.108[a]		0.070[a]		-0.007	
	(0.279)		(0.018)		(0.014)	
After × Monthly Income (10,000 PhPs)		-0.212		-0.010		0.041
		(0.451)		(0.027)		(0.052)
Household Size	1.667[a]		0.069[a]		0.001	
	(0.085)		(0.004)		(0.001)	
Employed Household Members	0.176		0.007		0.004[b]	
	(0.131)		(0.007)		(0.002)	
High Skilled Employment	-0.021		0.019		0.072[a]	
	(0.474)		(0.024)		(0.007)	
Subdivided House/Duplex	-1.342[a]		-0.070[a]		-0.043[a]	
	(0.403)		(0.024)		(0.007)	
Freestanding House	0.416		0.011		-0.017[b]	
	(0.335)		(0.019)		(0.007)	
Monthly Income (10,000 PhPs)		0.073		0.010		0.011
		(0.366)		(0.022)		(0.027)
Mean	19.83	19.83	2.80	2.80	0.16	0.16
Household FE	✓	✓	✓	✓		
Small Area FE					✓	✓
R^2	0.006	0.000	0.005	0.000	0.026	-0.003
N	4,004,445	501,075	4,004,445	501,075	48,982	6,034
Dataset	Billing Panel	Billing Panel	Billing Panel	Billing Panel	Household Survey	Household Survey

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects. Standard errors are clustered at the small-area level (in parentheses). The water service area is divided into 2,974 small-areas. [c] $p<0.10$,[b] $p<0.05$,[a] $p<0.01$ 45 PhP = 1 USD

water production except pipe replacements. Except for the *profit-maximization* counterfactual where the firm enjoys any profits from pipe investments, any cost savings or cost overruns as a result of the pipe replacements are assumed to be passed on to consumers in the form of fixed rebates or charges, which do not affect consumers' marginal incentives to consume water. Pipe replacements are assumed to be independent of operating costs such as labor or maintenance expenditures.

The *full-information* counterfactual simulates how often a regulator would optimally replace pipes in order to maximize welfare under full information. For each zone of the service area, the regulator maximizes present-discounted consumer welfare indefinitely given by the following expression

$$
\begin{aligned}
max_{R_t \in \{0,1\}} \; \sum_{\tau=t}^{\infty} (1+\delta)^{t-\tau} [CS(k_t) + V(k_t)] \\
V(k_t) &= W(k_t) - E(k_t) - L(k_t) \\
k_{t+1} &= (1+k_t)\,(1 - R_t \mathbb{1}\{k_t > l\}) \\
L(k_t) &= \frac{r(1+r)^l}{(1+r)^l - 1} \overline{L}\, \mathbb{1}\{k_t \le l\}
\end{aligned}
$$

where t indexes month. δ is the discount factor which is assumed to be 5% in annual terms (0.42% in monthly terms). k_t is the age of the pipes. $CS(k_t)$ is the consumer surplus from pipe replacements as defined in equation (5), which is assumed to be decreasing in pipe age. $V(k_t)$ is the net revenue from pipe replacements, which depends on revenue from (increased) water sales, $W(k_t)$, costs of water leakage, $E(k_t)$, and payments on any loans to fund pipe replacements, $L(k_t)$. $V(k_t)$ is passed on to consumers as a fixed rebate or charge (ie. by adjusting the monthly service charge). Due to pipe deterioration, consumer surplus and water revenue are both assumed to be decreasing in pipe age while water leakage is assumed to increase with pipe page.

Each month, the regulator chooses whether to replace pipes ($R_t = 1$) or not ($R_t = 0$). Replacing pipes sets the pipe age, k_t, back to zero and is only possible if the regulator has paid off any debt from a previous pipe replacement where l indexes the duration of the debt. The regulator is assumed to fund a pipe replacement with a loan of total size, $\overline{L}$, at monthly interest rate, r, over duration, l. r is assumed to equal 5% in annual terms (0.42% in monthly terms), consistent with the terms of the loans currently held by the water company. l is assumed to equal 5 years, which provides a lower bound on the replacement frequency. The expression for $L(k_t)$ calculates the size of the monthly loan payments. In this framework, the optimal schedule of pipe replacements balances net revenue against consumer surplus from new pipes.

In the *regular-replacement* counterfactual, the regulator only observes the age of the pipes and chooses to replace pipes as soon as they reach a certain age, $\overline{K}$. In the *quality-standards* counterfactual, the regulator also observes the water pressure reaching consumers, $P(k_t)$. The regulator then chooses to replace pipes once the water pressure falls below a certain threshold, $\overline{P}$. In the *cost-minimization* counterfactual, the regulator does not observe water pressure, but instead observes leakage costs. The regulator then replaces pipes to minimize leakage costs, $E(k_t)$ and pipe replacement costs, $L(k_t)$.

In the *profit-maximization* counterfactual, the regulated firm is assumed to be fully aware of not only leakage costs, $E(k_t)$, but also revenue from water sales as result of pipe replacements, $W(k_t)$. To incentivize the firm to act on this information, the regulator allows the firm to enjoy the net revenues from pipe replacements, $V(k_t)$. The firm then chooses replacement rates to maximize, $V(k_t)$. In this case, consumer surplus, $CS(k_t)$ is equal to consumer welfare because consumers no longer receive transfers equal to net revenues. This arrangement is similar to "price-cap" regulation where the regulator sets a maximum price and the firm is able to enjoy profits at prices up to the maximum while incurring investment costs.[23]

7.2. Empirical Inputs

The counterfactuals have four key empirical inputs: consumer surplus, $CS(k_t)$, revenue, $W(k_t)$, leakage savings, $-E(k_t)$, water pressure, $P(k_t)$, and replacement costs, $\overline{L}$. The first four inputs depend on pipe age. The counterfactuals assume that each of these inputs declines at a linear rate with pipe age. This assumption is consistent with a linear decay over time in the effect of pipe replacements on water use as observed in Table 3. The rate of decay is measured by the effect of pipe replacements on each input. The effect of pipe replacements measures the difference between new pipes and old pipes that have already decayed for 25 years (or 300 months). Each input is then summarized as $G(k_t) = \frac{k_t}{330}\Delta g$ where Δg is the estimated pipe replacement effect for each input, g. This expression normalizes the intercept to zero.

The empirical inputs are estimated separately for 11 different zones of the service area in order to capture how regulators may tailor their policies to particular areas of the service area. The zones meet the criteria of having at least 50 households observed in the connection survey both before and 1 to 3 years after pipe replacement projects. These zones come from the set of geographic areas that the water utility uses to determine regional policies. The zones account for 46% of the total sample and aim to capture geographic heterogeneity while still ensuring there are enough observations in each zone to reliably estimate the effects of pipe replacements.

The effects of pipe replacements are estimated for each zone using the following

[23] See Joskow [2007].

equation

$$y_{itl} = \sum_{z=0}^{11} \psi_1^z \,\text{Post Pipe (1 to 3 yrs)}_{tl}^z \;+\; \psi_2^z \,\text{Post Pipe (0 or 4+ yrs)}_{tl}^z + \psi_t + \psi_i + \varepsilon_{itl} \qquad (10)$$

where z indexes the 11 zones of interest (with all other zones collapsed into $z = 0$). y_{itl} is the outcome measured at the household, month, and small-area level. ψ_1^z is the coefficient of interest for zone z capturing the difference in outcomes between old pipes and newly installed pipes (ie. $\frac{dG}{dR}$) by focusing on 1 to 3 years after replacement. Measuring effects for this time window intends to ensure that there is a large enough sample to precisely measure impacts for each outcome while omitting the year of replacement (when effects are still ramping up) and later years (when pipes begin degrading). ψ_2^z controls for differences in outcomes at years 0 (the year of replacement), 4, 5, or 6 after pipe replacement for each zone. ψ_t and ψ_i include calendar month and household fixed effects respectively.

Table 5 reports the estimated effects across the 11 zones on booster pump use, water use, household and commercial water bills, and households reporting low pressure. These estimates allow for measuring the effects of pipe replacements on consumer surplus and revenue captured in Table 6.

7.2.1. Consumer Surplus

Consumer surplus with respect to pipe age, $CS(k_t)$, depends on the effect of pipe replacements on water use and booster pump use. The first and second columns of Table 5 reports these effects separately by zone. Effects range widely across zones spanning from -7 to -59 percentage point declines in booster pump use and from 4.7 to 1.7 cubic meter increases in monthly household water use. This heterogeneity may be driven by differences in preferences for quality service and/or by differential rates of pipe deterioration across areas.

Combining these effects with earlier estimates of the price sensitivity (0.6) and cost of booster pumps (486 PhP/month) according to equation (5) yields the effect of pipe replacements on consumer surplus (ie. Δcs) captured in column (1) of Table 6.

7.2.2. Revenue

Revenue with respect to pipe age, $W(k_t)$, depends on the effect of pipe replacements on total revenue including both revenues earned per household and per commercial water

Table 5. Effects of Pipe Replacements by Zone

Zone	(1) Booster Pump Use	(2) Water Use	(3) Household Revenues	(4) Commercial Revenues	(5) Low Pressure
1	-0.36[a]	2.60[a]	57.79[a]	-12.73	-0.37[a]
	(0.03)	(0.40)	(14.55)	(74.65)	(0.06)
2	-0.15[a]	2.19[a]	87.49[a]	104.77	-0.11[c]
	(0.03)	(0.27)	(10.82)	(73.34)	(0.06)
3	-0.28[a]	1.31[b]	47.99[b]	166.02	-0.16[b]
	(0.05)	(0.52)	(19.72)	(102.79)	(0.08)
4	-0.33[a]	2.46[a]	57.35[a]	100.31	-0.28[a]
	(0.03)	(0.33)	(11.42)	(83.67)	(0.06)
5	-0.48[a]	4.22[a]	143.19[a]	-4.40	-0.28[b]
	(0.08)	(0.63)	(24.02)	(169.95)	(0.12)
6	-0.27[a]	3.41[a]	71.55[a]	72.78	-0.32[a]
	(0.05)	(0.48)	(17.41)	(115.87)	(0.07)
7	-0.35[a]	3.63[a]	85.95[a]	-18.07	-0.25[c]
	(0.08)	(0.58)	(21.20)	(106.65)	(0.14)
8	-0.59[a]	4.70[a]	100.27[a]	-141.87[c]	-0.56[a]
	(0.06)	(0.65)	(23.84)	(74.94)	(0.10)
9	-0.07	2.47[a]	132.97[a]	280.68[a]	-0.00
	(0.04)	(0.57)	(21.14)	(99.61)	(0.05)
10	-0.24[a]	1.67[a]	77.89[a]	266.86[a]	-0.25[a]
	(0.04)	(0.40)	(14.92)	(46.76)	(0.07)
11	-0.54[a]	2.84[a]	136.45[a]	364.77[a]	-0.34[a]
	(0.03)	(0.47)	(18.41)	(86.29)	(0.05)
R^2	0.345	0.554	0.511	0.641	0.375
N	48,982	4,004,464	4,002,952	3,093,439	48,982

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

connection. The third and fourth columns of Table 5 report these effects separately by zone.[24] Effects on revenues from households in column (3) are roughly proportional

[24]The revenue measure for commercial connections keeps only observations between 0 and 10,000 PhP to account for potential bias of outliers because the distribution has a long right tail and large billing errors/corrections, which removes 9% of the observations.

Table 6. Welfare Inputs by Zone

Zone	(1) Share of Population	(2) ΔConsumer Surplus	(3) ΔTotal Revenue	(4) ΔLeakage Savings	(5) Replacement Costs
1	0.12	271	55	188	7,696
2	0.12	148	99	188	7,913
3	0.09	186	65	188	4,551
4	0.12	247	81	188	7,671
5	0.10	373	143	188	8,856
6	0.09	249	80	188	7,425
7	0.04	287	83	188	9,663
8	0.04	434	68	188	10,639
9	0.10	121	203	188	11,685
10	0.05	176	126	188	6,112
11	0.13	358	189	188	6,822

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

to the effect on water usage in column (2).[25] Column (4) of Table 5 includes results for commercial water connections, which range from small shops to large factories. In some zones, commercial effects are large and positive while in other zones, results are close to zero or even below zero. Small effects may be explained by private investments in pumping stations by commercial entities. Negative coefficients may be explained by large concentrations of water refilling stations in particular zones. Composing over 5% of commercial connections, water refilling stations filter and bottle piped water for resale, serving as possible substitutes to high quality tap water.

Column (2) of Table 6 calculates the effect of pipe replacements on revenue (ie. Δw) by adding effects on revenues per household and effects on revenues per commercial connection weighted by commercial connections per household in each zone. On average for each household, there are around 0.18 commercial connections.

[25]Differences are likely due to the fact that the non-linear structure of the water tariff, which causes high-use households to be exposed to higher marginal prices.

7.2.3. Leakage Savings

Leakage savings with respect to pipe age, $-E(k_t)$ depend on the extent to which pipe replacements reduce the amount of water leaking from pipes. Pipe leakage is measured by comparing the amount of water supplied before and after pipe replacements. Water supply is measured at the monthly level for 1,242 hydrological areas for a total of 64,844 area-month observations.[26] The relatively small sample prevents estimation of zone-specific leakage rates. Therefore, the estimation assumes that all zones experience the same average reduction in leakage as a result of pipe replacements. Table 7 reports results on water supply from estimating equation (10) without heterogeneous effects by zone. Pipe replacement projects are associated with a statistically significant drop in water supplied of around 38 m3 per household. Given that the average household uses around 20 m3, this effect suggests that before pipe replacements, the utility loses at least two units of water for every one unit that reaches households. The water company approximates that the marginal cost of supplying water is around 5 PhP/m3. This approximation suggests substantial leakage savings equal to 188 PhP per household/month as reported in Column (4) of Table 6.

Table 7. Effects of Pipe Replacements on Leakage

	(1) Water Supply
After Pipe Replacement	-37.51[a]
	(10.30)
Mean	46.85
R^2	0.880
N	63,546

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

[26]The technology and infrastructure to measure water supply was gradually introduced across different areas during the sample period creating an unbalanced panel of supply measurements. Water supply is also measured per household by dividing total water supply by the total number of water connections in each area multiplied by the average number of households per connection in each area.

7.2.4. Water Pressure

Water pressure with respect to pipe age, $P(k_t)$ depends on the extent to which pipe replacements affect reported water flow. Water pressure is measured according to the connection survey, which asks if households do not have water pressure between 6 pm and midnight (when not using a booster pump). Column (5) of Table 5 reports effects on this indicator variable for each zone. Pipe replacements reduce the share of households reporting no water pressure across all zones with effects ranging widely from a 56 percentage points in zone 8 to less than 1 percentage point in zone 9. Heterogeneous effects may be driven by different rates of infrastructure degradation due to geology, road maintenance, or recent construction. Different effects may also be driven by proximity to nearby pumping stations which determine water continuity. Effects on water pressure appear roughly correlated with effects on outcomes in the first four columns of Table 5.

7.2.5. Replacement Costs

For each hydrological area, pipe replacement project records include the total project costs and total kilometers of replaced pipes. Project costs per household in each zone are calculated by multiplying the average cost per kilometer of piping by the kilometers of pipe replaced per household. Column (5) of Table 6 presents project costs in terms of PhP per household. Costs range from 6,112 for zone 10 to 11,685 for zone 9. Differences in costs across zones likely stem from variations in the material and diameter of pipes needed for different areas as well as local housing densities. Costs appear only loosely correlated with consumer surplus and total revenue changes, which suggests that strictly minimizing replacement costs may not maximize total welfare. The counterfactuals assume an annual interest rate of $r = 5\%$, which is the rate for many of the water company's current loans. Given the interest rate, loan payments, $L(k_t)$, necessary to fund the project costs are calculated for each zone.

7.3. Counterfactual Results

DO MORE TO PUT THE SIZES IN CONTEXT!! [average bill, etc.!]

For each counterfactual, the simulations compute the optimal frequency of pipe replacements (in years) as well as the welfare deviations from the optimal, full-information benchmark. Table 8 presents average results across all zones while Table 9 includes counterfactual results for each zone separately. According to column (1), the optimal frequency of pipe replacements for the full information benchmark is 9 years on average (Table 8) and ranges between 7 and 11 years for particular zones (Table 9).

Column (2) includes results for the strategy of replacing all pipes every 25 years. This strategy roughly approximates the context in Manila where the regulated company replaced most of the pipes had been installed by the public utility 25 years ago. This strategy results in replacing pipes around 2.5 less frequent that the full-information benchmark. Row "Δ Total Surplus" measures the change in total surplus relative to the full-information benchmark in column (1) where surplus is measured in terms of PhP per household/month. Across all zones on average, replacements every 25 years lower welfare by 97 PhP per household/month relative to the full-information benchmark.

Row "Δ Cons. Surplus" measures the change in surplus attributable to consumer utility from water use and booster pump expenditures (as described by equation (5)). The average decline in consumer surplus is almost as large as the total decline in welfare which suggests that most of the costs of infrequent pipe replacements are borne directly by consumers in the form of poor quality water consumption and increased booster pump expenditure. Under the assumption that the regulator is able to pass on any cost savings/overruns onto consumers, consumer welfare is equal to total surplus. This assumption is likely to hold for counterfactuals in columns (1) to (5).

Table 8. Counterfactual Results

	(1) Full info	(2) Every 25 yrs	(3) Pressure <90%	(4) Pressure <80%	(5) Cost min	(6) Profit max
Full Sample						
Freq. (yrs)	8	25	13	21	15	12
Δ Total Surplus	—	-97	-42	-79	-31	-11
Δ Cons. Surplus	—	-70	-4	-37	-31	-15
Without Zone 9						
Freq. (yrs)	8	25	9	18	15	12
Δ Total Surplus	—	-101	-19	-60	-30	-11
Δ Cons. Surplus	—	-75	4	-33	-33	-17

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

Table 9 indicates large heterogeneity in welfare impacts across zones. Table 9 lists

Table 9. Counterfactual Results by Zone

Zone	(1) Full info	(2) Every 25 yrs	(3) Pressure <10%	(4) Pressure <20%	(5) Cost min	(6) Profit max
1	9	25	5	12	15	13
		[-87,-72]	[-23,17]	[-14,-15]	[-23,-31]	[-15,-20]
2	9	25	18	40	15	12
		[-62,-38]	[-34,-22]	[-200,-89]	[-12,-15]	[-3,-6]
3	7	25	16	31	11	9
		[-90,-55]	[-36,-27]	[-127,-70]	[-11,-13]	[-5,-7]
4	8	25	8	17	15	12
		[-88,-66]	[-3,4]	[-38,-33]	[-25,-28]	[-12,-14]
5	8	25	5	5	16	12
		[-131,-106]	[-20,19]	[-20,19]	[-48,-53]	[-16,-25]
6	8	25	5	10	14	12
		[-90,-67]	[-22,17]	[-5,-7]	[-25,-28]	[-11,-13]
7	9	25	8	18	17	14
		[-82,-75]	[-2,6]	[-43,-43]	[-29,-37]	[-13,-27]
8	9	25	5	8	18	15
		[-114,-115]	[-34,31]	[-3,2]	[-57,-66]	[-31,-49]
9	11	25	50	50	19	12
		[-65,-27]	[-243,-76]	[-243,-76]	[-40,-16]	[-10,-3]
10	8	25	8	18	13	10
		[-92,-51]	[-2,-1]	[-50,-31]	[-20,-18]	[-4,-7]
11	7	25	5	12	14	9
		[-159,-110]	[-9,11]	[-35,-34]	[-56,-52]	[-13,-18]

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

the "Δ Total Surplus" and "Δ Cons. Surplus" respectively in parentheses below the replacement years. While 25 year replacements reduce welfare by under 65 PhP per household/month in zones 2 and 5, the same policy lowers welfare by at least 130 PhP in zones 5 and 11. Columns (3) and (4) present counterfactuals where pipes are replaced when the share of households reporting at least some water pressure falls below 90% and 80% respectively. Zone 9 never reaches these thresholds within 50 years because pipe replacements are estimated to have zero effect on reported water pressure in this zone (Table 5). Therefore, the counterfactuals assume that pipes in Zone 9 are replaced every 50 years. To account for Zone 9 being an outlier, Table 8 provides results for the full set of zones and for all zones except Zone 9.

Column (3) finds that the strict 90% threshold results in an average replacement frequency of 13 years and a drop in total surplus of only 42 PhP per household/month, which is less than half of the surplus change in Column (2). Table 9 reveals substantial heterogeneity in replacement frequencies: four of the zones are constrained by the minimum 5-year rate while three of the zones exceed 15-year rates. These replacement frequencies appear at least somewhat correlated with the frequencies in the full-information benchmark, which suggests that quality standards may provide a useful signal of welfare.

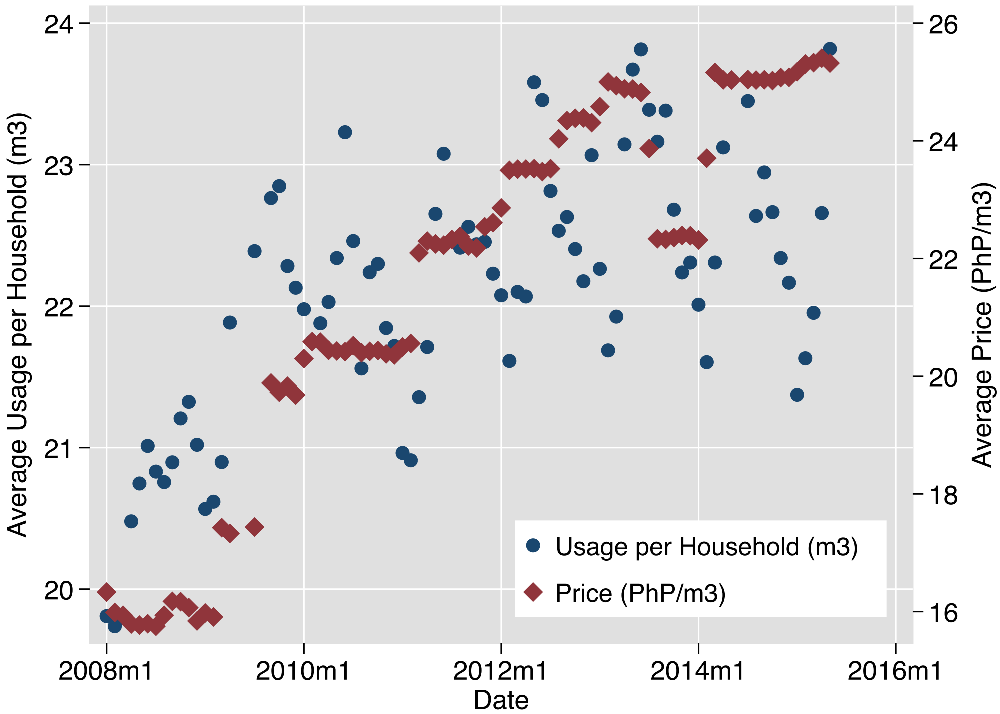
Column (4) tests a looser threshold of 80%, which almost doubles the average welfare loss of the strict threshold in column (3). Moving from the strict to loose threshold increases the average replacement frequency from 13 years to 21 years. These findings indicate that welfare effects are very sensitive to the quality standards chosen by the regulator.

Excluding Zone 9 from average results in the second panel of Table 8 improves total welfare by around 20 PhP per household/month relative to the first panel for both columns (3) and (4). These results suggest that policies based on quality standards may be sensitive to outliers and/or the precision of pressure measurements.

Column (5) presents the cost-minimization counterfactual where the replacement frequency is chosen to minimize pipe replacement costs and water leakage costs. The cost-minimization counterfactual results in an average replacement frequency of 15 years. Although this replacement frequency is roughly double the benchmark freqency, welfare is only 31 PhP lower than the benchmark. Table 9 finds that the relative replacement frequencies across zones are similar between the cost-minimization counterfactual and the benchmark.

Column (6) provides results for the profit maximization counterfactual where the replacement frequency is chosen to maximize revenue net of costs. Profit maximization results in an average replacement frequency of 12 years. Total surplus is only 12

Figure 3. Price Time-Series



PhP per household/month lower than the optimal benchmark, which is the smallest average gap across counterfactuals. In practice, the regulator is likely to allow the water company to enjoy profits from these investments as a condition of implementing a profit maximization regime.[27] Therefore in this counterfactual, consumer welfare equals consumer surplus. The relative reduction in consumer surplus is still smaller than the relative reduction in total surplus across the other counterfactuals, which suggests that the profit maximization counterfactual is the optimal second-best policy.

Figure 4. Tariff Schedule

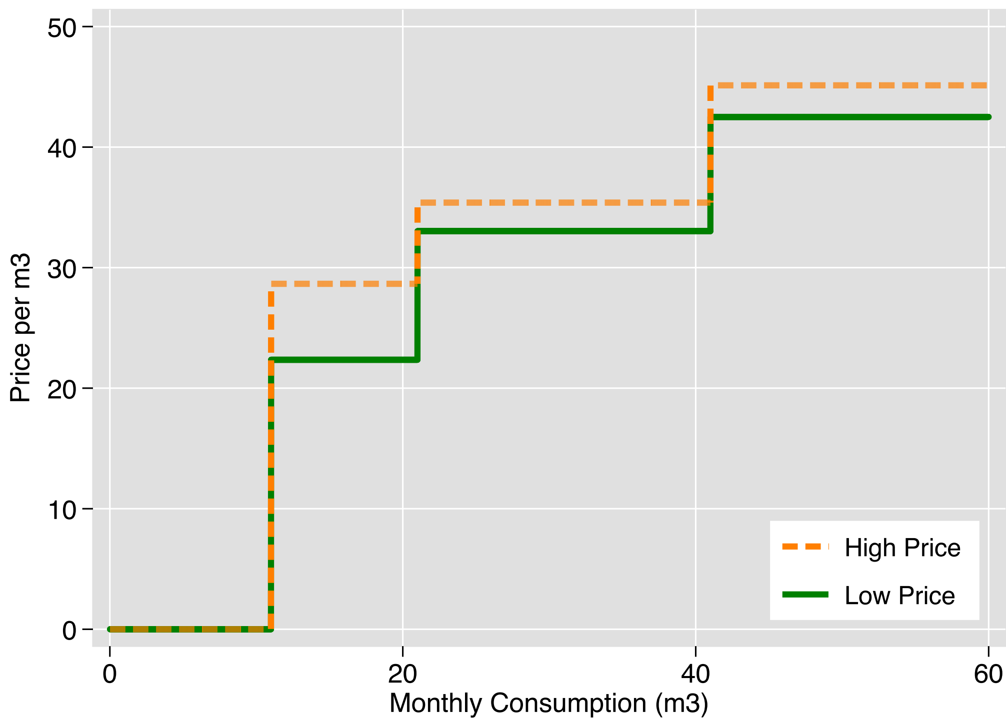


Figure 5. Usage Histogram

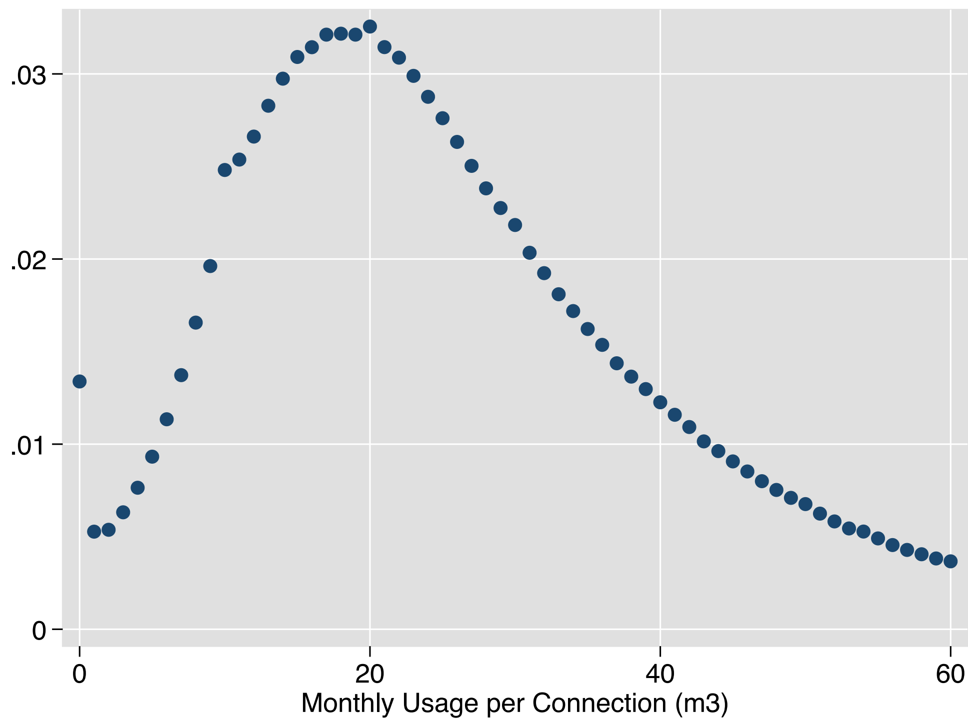


Table 10. First Stage and Reduced Form Estimates

	Water Use		Booster Pump Use	
	First Stage	Reduced Form	First Stage	Reduced Form
After Pipe Replacement	-0.01	2.02[a]	0.07	-0.22[a]
	(0.01)	(0.15)	(0.04)	(0.02)
Post Price Increase	4.65[a]	-2.74[a]	4.27[a]	-0.00
	(0.07)	(0.47)	(0.25)	(0.05)
Months Pre	0.01[a]	0.06[a]	0.01[a]	0.00
	(0.00)	(0.02)	(0.00)	(0.00)
Months Post	-0.02[a]	-0.02	-0.02	0.00
	(0.00)	(0.01)	(0.01)	(0.00)
R^2	0.986	0.554	0.690	0.335
N	4,004,445	4,004,464	48,982	48,982

Weighting, discussion of different samples, clustering, controls (especially rate classes). This table predicts usage per household with pipe replacement and price with different fixed effects.

8. Conclusion

9. Appendix

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[27] For example, the regulator may set a maximum price that takes into account other observable operating/fixed costs, and then allow the company to invest in its own pipe replacements while also capturing the profits.

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