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Key points:

- Half of the households either didn't reduce water usage or even increased water usage after a price was introduced.
- Household-level detailed water usage measurements, both before and after the introduction of water-price.
- Habits, baseline usage, ownership of residence, prior non-price intervention, and bill to pay period affect conservation outcomes.

Abstract

The introduction of a volumetric-pricing has been a critical intervention in household water conservation programs. However, it is typically impossible to observe how individual households respond to introducing a price signal as metering and billing start simultaneously. We report results from a near-ideal quasi field experiment wherein we measured daily water use both before and after the introduction of volumetric pricing (n = 59,563). As expected, the introduction of volumetric pricing (that replaced the previous fixed fee regime) resulted in an overall reduction in aggregate water use. However, the aggregate conservation effect of volumetric pricing (5%, $p<.01$) masks how nearly half of households increased water use. Further, a large share of households consuming above the median in the fixed price regime further increased water use. Using daily household-level water use data at three metered points for each household, we also detected that more than a third of all households increased water usage after the water bill was delivered. Triangulating our findings using multiple methods, including fixed effects panel and intervention time series, we also uncover key drivers of price response, such as water curtailment habits and a prior non-price intervention. The heterogeneous price response framework that we develop here reveals a large potential to design water conservation programs that combine price and non-price interventions to seal leaky water conservation buckets.

Plain Language Summary

We report a long-duration study in which water usage was measured for each household daily for more than a year before a volume-based billing was introduced. This observational setting provides a peek into previously unmeasured

phenomenon. A small fraction of the households (the top 12% of the households that reduced the most water usage) contributed as much as the entire net conservation effect. Another small fraction (the bottom 18% of the households that increased the most water usage) had as large a negative effect as the entire net conservation effect. If there were no households with a negative effect (i.e., if they had stayed at their level before the introduction of price), the net conservation would have been nearly two and a half times what we observed. These and other findings in this study reveal the need to further research and understand the heterogenous nature of household-level response to introduction to price. The study also reinforces the value of theoretically grounded non-price interventions for lasting conservation effects.

Introduction

After more than fifty years since it first came to the fore, the role of marginal volumetric pricing continues to be a central topic in water conservation research, policy, and praxis (Ornaghi & Tonin, 2021; Reynaud et al., 2018; Herrington, 1999; Howe & Linaweaver, 1967). Across numerous studies and resource sectors, it has been observed that the introduction of price for a product or service can be a robust demand reduction intervention, but there are also instances of increase in demand that suggest a risk of lasting resource wastage through adverse behavior (Gneezy & Rustichini, 2000; Gneezy et al., 2011). While the complex relationship between price and its effect continues to be under investigation, it has been recognized that marginal price or even salience or knowledge of price-information could lead to an adverse effect on resource conservation, possibly because users switchover to follow market norms in place of social norms (Pellerano et al., 2017; Frey & Oberholzer-Gee, 1997; Wichman, 2017; Carter & Milon, 2005). In the water sector, it has been found in many countries that metering and volumetric billing can also increase the financial hardship for the underserved segment of the population and diminish the concern for social equity and public goods (Mangold et al., 2014; Barraqué, 2011; Whittington, 1992). Residential water use behavior is influenced by a large number of household characteristics, the lag between consumption and bill, limits to demand elasticity, the level of price, and many other contextual factors (Braden et al., 2009; Hoque, 2014). Given these complexities, divergent potential effects of price, and their implications on conservation, it is no wonder that there is continued new research to observe, experiment, and understand the effects of water price on usage.

The behavioral response to price as a conservation policy instrument has been studied for the last several decades in water and other natural resource sectors (Addo et al., 2018; Brent & Ward, 2019; Ezzine-de-Blas et al., 2019; Hanke, 1970). Several key determinants of conservation behavior have been examined, including the role of habits and attitudes (Fielding et al., 2012; S. Russell & Fielding, 2010). This extensive literature confirms that while the aggregate response to the introduction of price could well be an overall reduction in usage, as seen in the aggregate level studies after the introduction of volumetric-price for water in prosperous cities around the world (Herrington, 1999), the potentially opposite direction of household-level response is usually not examined. Measurement of the volume of water drawn by a household usually starts simultaneously as usage-based billing. Cases of both adverse and favorable changes after the start of a priced-regime can be detected and analyzed to confirm this behavior if only such data were available. Likewise, the role of habits, baseline usage, and other household characteristics has not been researched under the introduction of price-signal. Recent research has recognized the importance of understanding the heterogeneity of household behavior through appropriate measurements and analysis and pointed to the considerable conservation potential that it can reveal (Bolger et al., 2019; Cominola et al., 2019; Kahneman et al., 2021; Pérez-Urdiales et al., 2016).

In the energy sector, it has been observed that events such as the arrival of a bill or information can lower energy use (Allcott & Rogers, 2014; Gilbert & Zivin, 2014). However, an increase in water usage has also been observed when billing frequency is increased, at least in one study in the southeastern US (Wichman, 2017). In this case, increased water use is explained primarily by a welfare gain by households through increased outdoor watering based on their perception of low-water price. In another study it was found that users with price knowledge increased water usage (Carter & Milon, 2005), similar to experiments in the energy sector where a lower actual cost than self-estimated cost led to increased consumption.

The large body of research notwithstanding, the potentially heterogenous effects of price on water conservation behavior across households, over time, or at critical events remains poorly understood. While some of the fluctuations can be random noise, understanding noise and reducing noise will provide ways to maximize the size of the conservation effect. Bridging these empirical gaps can result in an increased effect-size of price interventions and potentially ameliorate potential hardships that come with introducing price (Mangold et al., 2014; Barraqué, 2011; Whittington, 1992). The small size of effects of field interventions continues to be a significant concern (DellaVigna & Linos, 2020). The conservation effect size can be increased if the interventions are designed to incorporate ways to change the behavior of the largest number of users towards a consistently lower usage. Insights about the divergent nature of the response to price and its underlying drivers can directly help improve demand management policies and water conservation practices at homes.

One of the reasons for this lack of a clear understanding of the effect of price is the limitation of observations under ideal experimental settings (Price, 2014). Laboratory experiments are not well-suited to mimic actual water usage behavior within a household, given the large difference between perceived or self-estimated water use and actual water use, and also the large divergence in factor of people's estimates of water use (Attari, 2014; Fan et al., 2014). Field experiments have not been conducted to systematically record detailed observations under an ideal experimental setting with both before and after price-signal stages, control and treatment groups, and a long-duration with frequent measurement. Due to ethical and political considerations, it may not be possible to allocate price treatment and non-price control conditions to households randomly. However, it may be possible to observe usage in both before price and after price-signal stages through separation of the start of billing and metering. An early investment in metering and meter reading can help understand the heterogeneity of response to the introduction of price, but there are no such studies to the best of our knowledge. However, there have been some attempts to estimate the likely heterogeneity of response across households. A study from Abu Dhabi used the first billed month's water usage as a proxy of before-price stage's usage to estimate that 73% of households reduced usage in subsequent months (Abu Qdais & Al Nassay, 2001). Actual baseline measurements in the before-price stage and over-critical events would be more reliable and revealing. A better understanding of favorable and adverse responses in such studies can be invaluable to increase the overall effect, something that the aggregate treatment effect hides.

We report a long-duration quasi-experiment in which water usage was measured for each household daily for more than a year before volumetric billing for water at the household level was introduced. This novel observational setting provides a peek into several important research avenues: the nature of heterogeneity of response to the introduction of price, i.e., the distribution of decrease (a favorable response), increase (adverse response), or no-change in use. Along the temporal dimension, what was the response, such as an initial response that persisted or disappeared or a gradual build-up over time? What mattered more – the introduction of price-signal or the salience of bill communication?

More than a year before the start of the price regime, three groups of randomly assigned households received a non-price treatment designed to test persistent reduction in water usage, while the 4th group of households (group C0) served as a control [name deleted to maintain the integrity of the review process]. The three groups received incrementally more complete treatment with simplified usage information (group T1), suggested conservation goal (T2), and conservation tips (T3). This setting thus allowed us to examine a few more pertinent research questions on a combination of price and non-price interventions on the same set of households: did the three different non-price treatments affect the response to price favorably or adversely, and to what extent? How do these four differently treated groups of households differ in response to the same price intervention, and therefore which combination led to the lowest level of water use?

These and other aspects of our analysis answer several vital questions around previously unmeasured heterogeneity of response to the introduction of water-price. By measuring water curtailment habits and attitude towards water and environment, apart from the baseline level of usage and household characteristics, we also attempt to uncover the potential drivers of heterogeneous effects, similar to the emerging research for factors underlying non-price interventions (Brent et al., 2020).

Our analysis reveals that the net demand reduction in the priced-regime is smaller than the total reduction by the top 12% of the households who reduced the most. Nearly half of the households increased usage, while the rest (about 43%) reduced by a small amount or maintained their earlier level of water usage. We see this limited effect even though the price level at this community was higher than the highest prevailing market rate (i.e., the price of privately supplied water tankers). Using intervention time series analysis, we find no initial effect at the aggregate level after the start of priced-regime. Using intervention time series analysis at the household level, to our knowledge, for the first time in water conservation research, we observe a statistically significant increase in usage in 21% of the households. The reduction in the aggregate usage level started after the first bill-communication even though the start of pricing was communicated and well-explained, such as through information-only bills in the previous year (also *cf. SI 1.3. Introduction of price-signal*). We detect systematic heterogeneity of effects in various sub-groups by household characteristics such as water curtailment habits, number of residents, baseline usage, and property ownership. We note that the prior non-price intervention affected the result of price intervention in multiple ways and that the treated group with the complete non-price treatment reached the lowest level of water use.

In the next section, we examine the need to study the heterogeneous effects of price-signal that we examined in this study, followed by a description of the quasi-experiment, including the field setting and the diverse methods, before discussing our findings.

Maximum water conservation and heterogeneous effects

The determinants of water conservation behavior have been studied and modeled for price and non-price interventions. A reasonably comprehensive model is presented by (S. V. Russell & Knoeri, 2020), combining psychosocial and behavioral determinants. Their model also integrates findings from earlier literature (Fielding et al., 2012; Hoque, 2014; Klöckner, 2013; S. Russell & Fielding, 2010). However, from a water conservation maximization perspective, their model, and in general other such models, ignore two important determinants – the variation of behavior across time, and between households. The theoretical maximum conservation effect of an intervention is attained when each household uses the minimum amount of water all the time.

High variability of water usage across households and over time, especially towards relatively higher levels of water use, can be understood by measuring water usage at each household over time, analyzing the usage, and arriving at the determinants of variation that add to or detract from overall conservation. Our estimated price-effect is the primary measure of overall conservation in our quasi-experiment (see Figure 1). When a volumetric price was introduced instead of a fixed user fee, the new price-signal brought in a disincentive to consume. However, the aggregate price-effect hides divergence of response at the household level and the resultant lower magnitude of conservation. Thus, it is important to look for heterogeneous responses in various subsets of households (as shown in the figure) to find ways to grow the conservation effect-size.

Figure 1. The heterogeneous effects of price-signal are examined using four different types of effects. Effects are estimated for aggregates and various subsets of households (HH), time-periods, and a combination of the two. The diverse set of effects and favourable or adverse response within each type of effect reveal the nature of heterogeneous response.

Unfavorable responses to a price-signal by a specific household (even when the overall effect is to induce conservation) have remained largely unmeasured in the water sector. We are able to quantify this phenomenon through actual water use measurement, and as modeled estimates (household-level effects numbered 2, 3, and 4 in Figure 1). This characterization of household-level heterogeneity is important, as households may feel more entitled and perceive a right to consume when facing volumetric pricing (Frey & Oberholzer-Gee, 1997; Gneezy et al., 2011; Gneezy & Rustichini, 2000; Sachdeva et al., 2009). Reciprocity norm can set in – use water and pay the price – especially in an affluent community, where many paid services are consumed routinely. Recent empirical evidence also supports that households might respond with an increase in usage if the cost is perceived to be low (Brent & Ward, 2019), or when they are provided tips emphasizing lowering the cost through reduced usage (Asensio & Delmas, 2015). Since the price for water and energy tends to be small relative to income in affluent communities, it can encourage higher use when there is a switchover to market norms.

The persistence of an initial effect of price-signal over a long duration is central to the success of the price-intervention policy, and we study this through the time-dimension in price-effect and bill-effect. Water cost and water usage are usually opaque at the time of consumption; there is typically no information on usage or feedback at the time of use. As a result, there is inattention towards consumption and limited potential for cognitive processing of costs (Gilbert & Zivin, 2014). A periodic billing event creates only a temporary or dynamic salience due to its intermittent nature, but its effect depreciates after payment (Gourville & Soman, 1998). We measure the change in water usage between billing and payment days as bill-effect at the aggregate level and bill-impact at the household level.

A bill's salience effect can help people take water conservation actions, at least temporarily, perhaps even those gaining from the introduction of volumetric pricing in place of a fixed user fee. Salience can also work adversely towards conservation, possibly in the case of low-price, as seen in at least one water sector study where a higher frequency of billing was associated with increased usage (Wichman, 2017). We estimate this effect at the household level as bill-impact.

Heterogeneity within a diverse set of effects

We estimate four sets of effects (Figure 1) to answer our research questions about water use behavior in response to the introduction of price-signal:

(1) Price-effect: the price-signal's average treatment effect (ATE) on water usage, its divergence between the aggregate of all households and various subsets of households, and after each bill communication.

(2) Initial pattern: the best-fit pattern of the initial impact or response upon introducing the price-signal as seen in the time series of water usage.

(3) Size of impact: based on the initial pattern, the size of initial-effect and long-term effect of price-signal.

(4) Bill-effect: the salience and recency effect of bill communication till payment compared to other days in priced-stage (both in time series of water use and as ATE).

The effects 2, 3, and part of effect 4 (bill-impact) are based on time-series modeling and estimated at the household level (at various levels of aggregation). From a conservation perspective, these four effects can be either favorable (decrease in water usage) or adverse (increase). We also examine possible determinants of the observed effects and heterogeneity of effects.

Why examine heterogeneity of effects?

We lack a good understanding of the heterogeneous effects of introducing price-signal with no known empirical studies in the water sector that examine the nature of divergence of effects or the factors that explain the divergence. We turn to the literature from other sectors on heterogeneity in response to price and non-price treatments. The broader literature has recognized differences in the nature of individuals, characterizing them as sinners/saints or knaves/knights, and the temporal-reversal phenomenon (e.g., sinning saints) at an individual level (Le Grand, 1997; Sachdeva et al., 2009). More recently, there have been calls to appreciate the heterogeneity of judgment and decision-making, model this noise, and deal with it systematically for higher gains (Bolger et al., 2019; Kahneman et al., 2021; Pérez-Urdiales et al., 2016). So far, the noise aspect in household-level response has largely been ignored in the research to increase conservation effects though it can potentially contribute to increasing the effect size. Apart from a lack of suitable observational data measuring household-specific change after the start of priced-regime, the focus of price-change and tariff-change studies has also been more on the aggregate effect.

A large share of households in cities and new connections in rural areas do not pay a marginal price for water due to lack of metering (ADB, 2007; Hoque, 2014, pp. 53–54). Even when there is metering at the building level, there might be no metering at the dwelling-unit level. Further, large parts of the world are grappling with water scarcity issues (World Bank, 2016); they would especially benefit from the highest-possible conservation effect from a well-informed conservation policy design that combines non-price and price interventions. We contribute to the much-needed understanding of this phenomenon of heterogeneity of response, at household-level and over time periods, and explore ways to maximize conservation outcomes through persistent favorable water use behavior when metering or pricing is introduced. Using multiple methods and models, we supply empirical evidence needed to design public policies for water conservation.

The role of non-price interventions for water conservation is an active area of inquiry as seen in literature reviews (Koop et al., 2019; S. Russell & Fielding, 2010), but the behavioral aspects of price-interventions have scarcely been examined. The price-effect on households in a sequence of non-price intervention followed by the introduction of price-signal is a valuable observational setting; we estimate price-effect on both treated and untreated (control) households under the same setting.

Overall, there is limited research on the heterogeneity of behavioral response to the price signal, and there are no known studies with both before and after priced-regime observations. Our observational setting is near-ideal for research on the effects of price-signal, even though our observations are from a single residential community. The detailed observations from our quasi-experimental setting allow us to employ a new analysis framework towards an enhanced understanding of the effect of price-signal.

A quasi-experiment

Field setting

This study is based in an affluent community in Bengaluru, a fast-growing megacity in India, with persistent supply shortages and unequal social distribution of water (Mehta et al., 2013). The city's public water utility has been unable to meet the ever-growing demand for water. This community is situated at the outer periphery of the city, where most communities have to depend on private water supply from water tankers. Despite limited public supply, residents in most such communities experience round-the-clock water supply, thanks to their private distribution system within the residential complex. This community took several steps to conserve water, including rainwater harvesting, treatment of used water, and supply of treated water for toilet flush and gardens. The community decided to install water meters in each of the 120 apartment units so that it can introduce a volumetric bill for water and further reduce water usage. However, they faced several hurdles, including a lack of consensus among residents, choice of software for billing, and ownership of the proposed billing process.

These challenges led to a large gap between the installation of meters and the start of billing. This setting gave us a long-duration study with over two years of daily meter readings. We obtained permission from the property manager and the IRB that approved our study to conduct water demand reduction research (*cf. SI Figure S2 Consent Form*). Figure 2 summarizes the timeline and stages of the study.

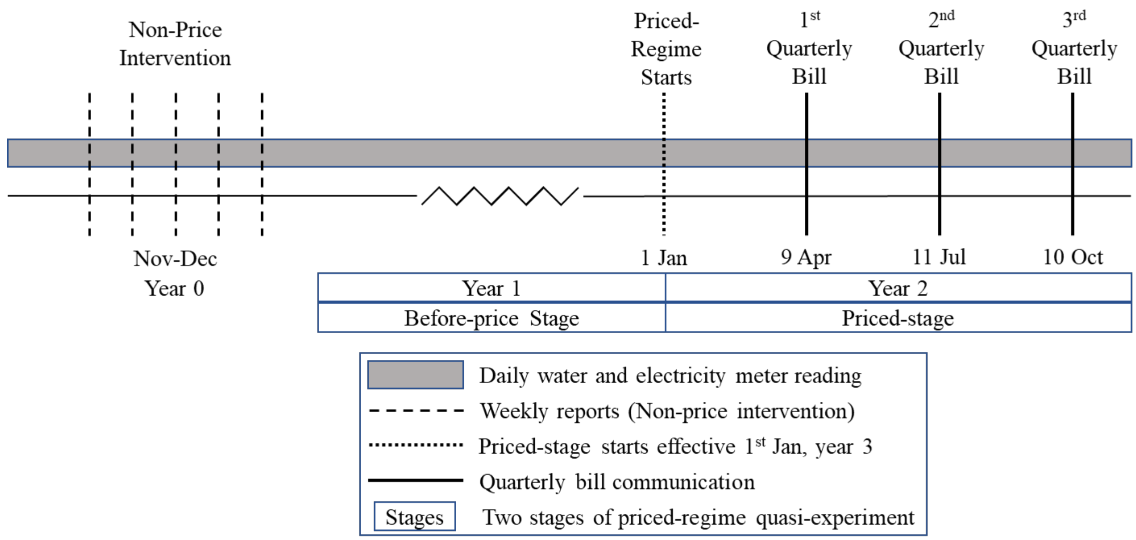

Figure 2. Timeline of the study over three calendar years in a residential community in Bangalore, India (N = 59,563 apartment-meter days for each of three water sub-meters and one electricity meter at 120 households).

Over a year before the start of the priced-regime, a brief non-price intervention was carried out on the part of the community. There was no non-price or price intervention in the next year (year 1 or 2017). Priced-stage started on the 1st of Jan of next (year 2, or 2018) and the 1st bill for water was communicated to residents on the 9th of Apr. A household survey was conducted after the start of billing, mainly towards the end of the study period. This survey timing also ensured that we collected near-final information on any variation in the number of residents (*cf. SI 2. Survey description and survey forms* for a detailed note how the data was finalized through the property management office).

This setting serves as a quasi-experiment with a before-after design. This natural setting made it possible to observe changes in water use behavior in the priced-stage compared to the before-price stage, for households that received a non-price intervention and for uncontaminated or untreated households from the control group non-price intervention.

Methods and models

We employ multiple methods and models to present triangulated findings. Fixed effects panel data analysis is performed on detailed daily water usage. Time series intervention analysis is performed on smoothened weekly data at household level and at various levels of aggregation of household. T-tests are carried out on before-price and priced-stage summary of household level water usage.

Panel data models for estimation of ATE

The price-effect is estimated as an ATE using the following panel data model where suffix i is for household (or apartment unit) and t is for day:

$$W_{\mathrm{it}} = \beta_0 + \beta_1 \mathrm{Priced}_t + \beta_2 \mathrm{Weekend}_t + \beta_3 \mathrm{Month}_t + \beta_4 \mathrm{Weather}_t + \beta_5 \mathrm{NoOfRes}_{\mathrm{it}} + \mathrm{FEHH}_i + e_{\mathrm{it}} \quad (1)$$

Thus, the main coefficient of interest is β_1 which gives us ATE. If W_{it} (water usage at apartment i on day t) is in lpcd (liters-per-capita-day), we get ATE in lpcd terms. If W_{it} is another usage variable, such as water usage in one of the three meters, it gives ATE in corresponding usage variable. We use this main model on various subsets of households and time-periods to estimate ATE for the subsets of interest. Also *cf. SI 3. Econometric models and statistical tests* for details of all the models.

The bill-effect is estimated using a similar panel data model. There are two important days for the salience of water usage, the day of bill communication and the payment due date. Accordingly, we define a dummy variable called bill-to-pay days as the period from the date of bill communication (usually around the 10^{th} of the first month of the quarter) to payment-due-date (towards the end of the same month). These days identify the period of the salience of water usage and bill. We modify our main panel data model to test for bill-effect. We replace the priced-stage dummy with a bill-to-pay days dummy. We use only priced-stage data to estimate the effect of bill-to-pay days as compared to other priced days.

Time series intervention analysis models

We use two different time series intervention analysis models to estimate effects at the two key milestones, the introduction of price-signal as a one-time regime-change and the quarterly bill communication. In both models, the number of residents in a household is incorporated in the dependent variable lpcd.

Initial impact pattern and its size Our objective is to study the initial and long-term effects of introducing a volumetric price on water use. We observe that the dependent variable lpcd in a household is serially correlated with possible seasonality. We study the effect of the introduction of price-signal using time-series methods to address this issue. We model the data using the autoregressive moving average (ARMA) model with intervention analysis. The ARMA structure of the model captures seasonality and temporal dependencies. The AMRA model combined with intervention analysis can assess the magnitude and the pattern of the intervention effect, as seen in other studies (Wakiyama et al., 2014).

The intervention analysis model (Box et al., 2015, pp. 481–485; Box & Tiao, 1975) has the following form:

$$Y_{\text{it}} = X_t^{'}\beta + \frac{\omega}{1 - \text{B}}\xi_t + N_{\text{it}} \qquad (2)$$

Y_{it} is the average water use in lpcd for apartment i in week t. X_t is a vector of weekly covariates (average temperature, humidity, rainfall, and a constant). $X_t^{'}$ represents transpose of X_t. The vector represents the regression coefficients. The term $(\frac{\omega}{(1-\delta B)})\xi_t$ represents the effects of the intervention in terms of the deterministic input series ξ_t and N_{it} is the noise which represents the observed series without the intervention effects. It is also assumed that N_{it} follows an ARMA(p, d, q). B is the backshift operator defined by $B(y_t) = y_{t-1}$.

The parameter ω is the initial-effect which measures the magnitude of intervention's effect beginning from the 1^{st} week of the priced-stage. A positive (negative) ω indicates that water use level has increased (decreased) after the intervention. δ stands for the decay parameter with the condition $|\delta| < 1$. This parameter indicates how long the effect remains in case of a transient effect, or how long the effect accumulates in the long run.

Using this model (equation 2) and two different deterministic input series, we study four intervention models that capture a combination of long-term / temporary effects and, increase / decrease in use. We refer to the four models as patterns - step, build-up, pulse, and decay. Step and build-up models depict permanent or long-term effects. The magnitude of the long-term effect is ω and $\frac{\omega}{(1-\delta)}$ for step and build-up models, respectively. Pulse and decay models have no long-term effect as these are transient effects.

Bill-impact: salience of bill to payment days We use the following times-series model for estimation of effect of salience of bill to payment days as bill-impact:

$$Y_{\text{it}} = \omega_1 I_1 + \omega_2\ I_2 + N_{\text{it}} \qquad (3)$$

I_1 equals one in the 1^{st} week after start of priced-regime and it is zero otherwise. I_2 equals one for the first three weeks after receiving bill and it is zero otherwise. These three weeks correspond to the quarterly bill to payment window. N_{it} is an ARMA process.

Scales used

The estimation of results is based on standard measurements, such as volume of water, number of residents, and average temperature for the day. In order to study the underlying drivers of the human behavior that we observe, these measurements are supplemented by a few scales that measure habits and attitudes.

A set of questions on self-reported water curtailment habits (such as how often do you close tap while brushing) is used as a water curtailment habits index. This list of questions was prepared based on questions used by other water-specific studies (Fielding et al., 2012; Koutiva et al., 2017; Pérez-Urdiales et al., 2016; Pérez-Urdiales & García-Valiñas, 2016) and then tailored to fit into out context.

We used New Ecological Paradigm (NEP) scale for measuring pro-environmental attitude, a widely used scale in water conservation studies (Attari, 2014; Corral-Verdugo et al., 2008; S. Russell & Fielding, 2010, pp. 3–5). As identified in by Dunlap Riley who created the NEP index (Dunlap, 2008), a person's attitude towards a specific resource is better measured through a scale specific to the resource. A new measure called water-NEP is created on lines of NEP to measure attitude towards water.

Also *cf. SI 2.1 Scales used* for details of the scales and tests of their reliability.

Descriptive statistics and results

We present descriptive statistics followed by estimated effects and heterogeneity of effects.

Descriptive statistics

We examine descriptive statistics at various levels of aggregation.

Given that the before-price stage is an entire year and the priced stage is almost a year (ten months) of the following year, any seasonal variation on water use is adequately accounted for in a simple before-after difference (especially given the moderate climate of Bangalore). Nevertheless, we repeated the tests using the same ten calendar months and found the results to hold. Further, when we look at liters-per-capita-day (lpcd) at the household level, the number of residents by date, the most important determinant of water usage, is also incorporated into the summary statistics.

Change in water usage

Table 1 shows that there is an average decrease of 4.7 lpcd (or 4%) of water usage in the priced-stage as compared to the before-price stage mean lpcd of 114.5. The change is statistically significant at 5% level. Most of the water usage occurs in the kitchen & utility area but the decrease is low in terms of statistical significance (10% level). Liters per day (lpd) reduces by nearly 12 liters (4%). Number of residents does not change materially.

Table 1

Summary of average water usage per household in the two staged of quasi-experiment.

Parameter	**Before-price**	**Priced-stage**	**Decrease**	**t-test (p-value)**
lpcd (liters per capita-day)	114.5	109.7	4.7	**0.02**
lpcd - Common Bathroom	23.7	22.6	1.1	0.16
lpcd - Master Bathroom	28.2	26.8	1.5	**0.01**
lpcd - Kitchen & Utility	62.6	60.4	2.1	0.06
lpd (liters per day)	318.9	307.0	11.9	**0.02**
No. of residents	*2.95*	*2.93*	*0.01*	*0.38*

Note: the p-value corresponds to one-sided t-test of significant difference (positive or negative).

Both increase and decrease in priced-stage The aggregate reduction in water usage in the community is 1,200 lpd, which is about 4 % of the baseline daily usage of 32 thousand liters. But if we examine the share of reduction by each household (Figure 3), we see enormous differences in direction and size of response. Moving from left to right on the chart in order of reducing contribution to conservation, we see that the total conservation by households that conserved touches almost two and a half times the final level (corresponding to 2,770 lpd) but it is brought down by households that detracted from conservation by as much as 1570 lpd (displayed in red). Out of 101 households, the 12 households (displayed in green) that contributed the most to water conservation add up to more than 1,200 lpd (100% on the y-axis). In other words, the change in rest of the households (i.e., 88% of the households) make no net contribution.

It's important to highlight that this distribution is not around the mean of the effect (a decrease of 4.7 lpd), which would be usual and to be expected. This distribution is around the change (0 lpd difference) on introduction of price-signal which should ideally be all in the same direction for maximum effect size. While some divergence is to be expected, this very large divergence is starkly different from the expected behavior as per price-theory.

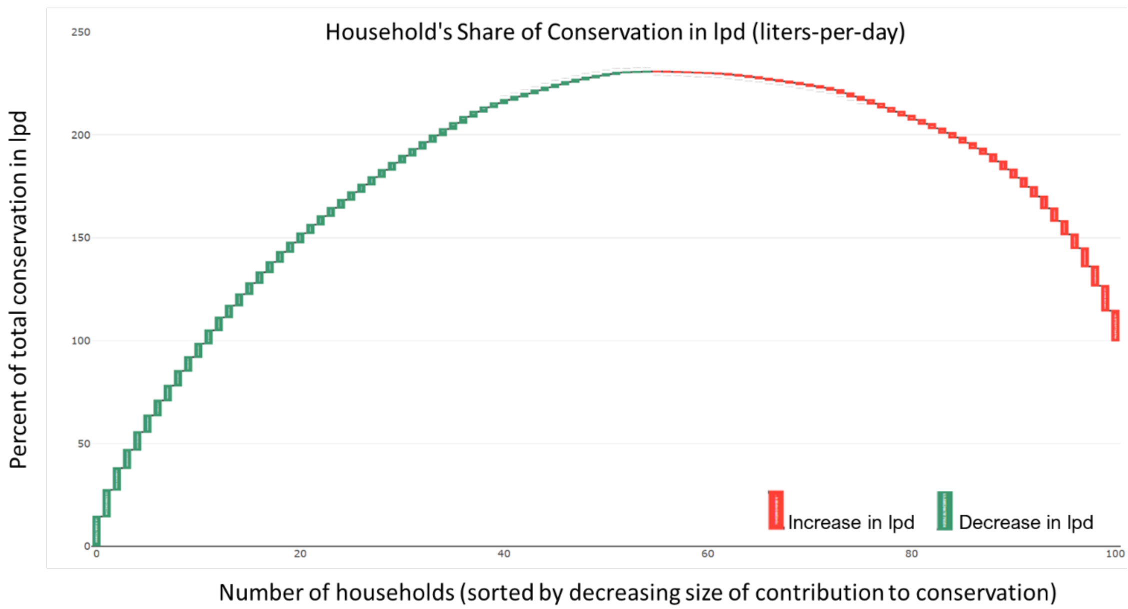

Figure 3. Large differences in contribution of households to net overall conservation. The top 12 households (out of 101) that reduced water use (shown in blue) contribute more than the net effect (100% line). Most households don't change significantly. Almost half of the households (shown in red) detract from total water conservation.

To examine this better, we look at the summary statistics again, but this time by dividing households into those who decreased lpcd and those who increased lpcd. Even at this highly aggregated level of data (Table 2), we are able to see that the households differ in terms of self-reported water curtailment habits, apart from level of water usage in lpcd and lpd.

Table 2

Comparison of households by direction of change in water usage

Parameters	Households that decreased lpcd	Households that increased lpcd
lpcd - before-price stage	122.4	104.7
lpcd - priced-stage	104.4	116.4
lpcd increase	-18.0	11.8
lpd - before-price stage	343.9	287.8
lpd - priced-stage	305.7	308.7
lpd increase	-38.3	20.9
No. of residents - before-price	3.00	2.87
No. of residents - priced-stage	3.10	2.72
Number of Bedrooms	2.73	2.84
Loss amount	836	897

Parameters	Households that decreased lpcd	Households that increased lpcd
Owners (% of households)	45%	44%
Payers (% of households)	70%	78%
NEP	3.75	3.73
Water NEP	3.96	3.94
Water Habits	*3.58*	*3.82*
Income	3.78	3.73

Note: Comparison of households that decreased lpcd with those that increased lpcd on introduction of price-signal. 45 households increased out of 101. The parameter values are averages. The p-values correspond to one-sided t-test of difference (positive or negative). We see that they differ only in baseline usage (lpcd and lpd) and in water curtailment habits.

Nearly half (45%) of the households increased lpcd with a large average increase of 11.8 lpcd. Even when we exclude households with a small size of change, this share does not change (e.g., if we exclude households with a change smaller than ±3 lpcd, 43% of such households increase lpcd). When we exclude cases of extreme change, again the share remains unchanged (e.g., if we exclude those with more than ±100 lpcd change, 45% increase).

A similar pattern is observed in lpd. 46% of households increased usage with an average of 34 lpd as compared to 50 lpd of decrease by 54% of households. If we exclude households with a small size of change, the share of increase changes marginally (e.g., 38% if we limit to more than ±10 lpd change). When large changes are excluded, there is no change in this share (e.g., if we limit to less than ±100 lpd change, 46% increase).

We observe that a large proportion of households increase water usage after introduction of price, and that this set's average usage was relatively low in the before-price stage. It is important to note that the level of water-price is about as high as reasonably possible for the property management under current social norms. Their average price is marginally higher than the purchase price of their dominant source of water – private water tankers, which are the costliest of the three sources they use. The other two sources - groundwater and rainwater harvesting – are virtually free after initial capital investment. Also, the household water bill is a relatively small share of resident's income, only about 0.6% of the average self-reported income (and ranging from 0.2% to 2%). But a much higher price may not be possible under the prevalent market price of water and the general expectation to charge as per cost. The management also employed an increasing block tariff structure to encourage water conservation by high users (*cf. SI Introduction of price-signal* for details of water tariff and a sample bill).

Role of usage in before-price stage Those who increased water usage were on an average relatively low water users, both in lpcd and lpd (Table 2).

However, many of the households that were already high-users further increased usage (Figure 4). In the low-users subset of households, we also see a decrease in lpcd by a large share of households. This shows presence of large divergence in behavioral response to the same price-signal.

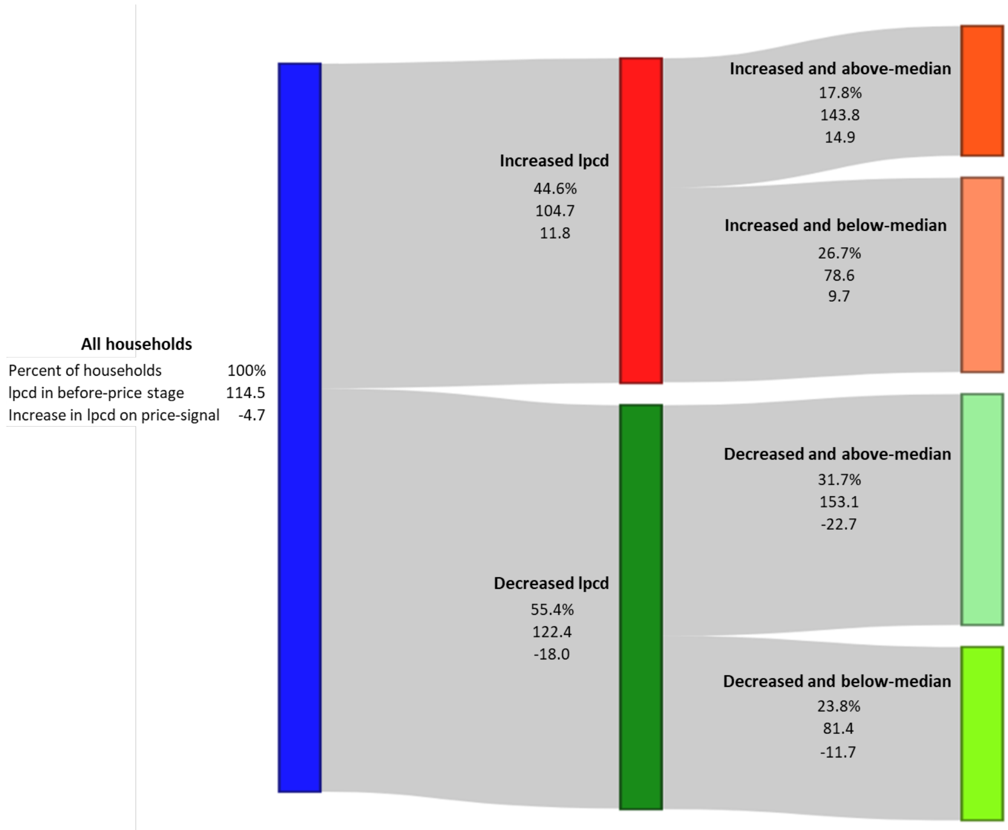

Figure 4. Change in lpcd on introduction of water-price summarized by subset of households based on response (increase/decrease) and level of water use (above/below median). First bifurcation of swim-lane is based on increase/decrease in lpcd. Second bifurcation is based on position of each household as above/below median lpcd level in the before-price stage. The response supports an adverse effect on high-users (+14.9 lpcd in top right swim-lane) and a favorable effect on low-users (-11.7 lpcd in the bottom-right swim-lane).

If we look at lpd average values in place of lpcd values, we observe the same pattern. While the aggregate response of households is in the expected direction, a very large subset of households show a response that is not only far away from the average response, it is in the opposite direction, even though many of them were above the median level of water use.

Role of habits and attitude towards environment and water

We divide the households into two - those above and below the median level of their self-reported water curtailment habits (Table 3).

Table 3

Summary of change in water usage by level of water habit

Households	Before-price	Priced-stage	Decrease	t-test (p-value)
Panel A. All households				
Low-habit lpcd (L)	118.0	113.3	-4.7	0.07
High-habit lpcd (H)	107.6	103.2	-4.4	0.14
Difference (L-H)	10.4	10.1	-0.3	
t-test of difference (p-value)	0.14	0.11	0.48	
Panel B. Treated households				
Low-habit lpcd (L)	115.2	110.4	-4.8	0.14
High-habit lpcd (H)	93.9	90.8	-3.1	0.17
Difference (L-H)	21.2	19.5	-1.7	
t-test of difference (p-value)	**0.02**	**0.02**	0.38	

Note: Summary of lpcd and change in lpcd by level of self-reported water curtailment habits; low and high refer to below and above median level in the population. The panel A is for all households and the panel B is for treated households (i.e., they had received a non-price treatment). The treated households show a strong difference in water usage based on level of water habits.

The households with lower water curtailment habits use more water, both before and after the introduction of water-price. If we look at only the households that received a prior non-price treatment, this difference is larger and statistically significant. The households that were primed by non-price treatment also have a higher negative correlation (-0.34) between their before-price lpcd and habit score as compared to the untreated households (-0.15). This suggests that the non-price treatment (which was a weekly water usage report repeated over 5 weeks) improved the reliability of their score on water curtailment habits index. The role of habits is clearer in treated households.

A priming effect from non-price treatment is also seen in scores of NEP and WNEP, our measures of attitude towards environment and water, respectively. However, the correlation is positive and correlations are weak. The untreated households with above median score of these two attitudes consume more water in the baseline stage, revealing a gap between attitude and behavior (*cf. SI 4.1.1 Water habits, NEP and Water NEP*). This gap is seen only in the untreated households suggesting that the non-price treatment has helped bridge the gap between attitude and behavior. The introduction of price-signal did not help bridge this gap in untreated households. The gaps are especially large amongst high-NEP households regardless of treated or untreated status

Owner-tenant The descriptive statistics show that owners of residence use relatively less water per day, both in lpd and in lpcd terms (*cf. SI 4.1.2 Owner-tenant*). Owners also reduced their per-day usage on introduction of price-signal, both in lpd and lpcd terms. But tenants hardly changed their lpd usage. As a result, the level of usage of water remained relatively high for tenants after introduction of price-signal, both in lpd and lpcd terms.

Role of prior non-price treatment

The summary statistics by group from the prior non-price treatment support that there was a reduction in water usage in three of the groups (C0, T1 and T3) despite very different levels of usage in the before-price stage (Table 4). The group T2 had a very low lpd and it did not reduce further. Households that moved in post the non-price intervention (column PI) also did not reduce despite starting at same level of lpcd and lpd as the average; this is explained by low ownership. Only one of them (or 5% of the group) is an owner whereas other groups have nearly 50% owners. The lowest lpcd is seen in the group T3, the only group using less than 100 lpcd of water.

Table 4

Summary statistics by groups from the prior non-price intervention.

Parameters and group	C0	T1	T2	T3	PI	All
lpcd - before-price	139	111	105	103	113	114
lpcd - priced-stage	130	103	103	99	112	110
lpcd increase	-9	-8	-1	-4	-1	-5
lpd - before-price	363	347	244	323	323	319
lpd - priced-stage	340	320	246	305	327	307
lpd increase	-22	-27	2	-18	4	-12
Number of households	21	21	22	17	20	101
Number of owners	10	10	8	11	1	40

Note: C0 is the control group that did not receive a treatment, and Ti are the three treated groups with incrementally stronger intervention. PI (post-intervention) refers to households that moved in after the end of delivery of non-price treatment to households.

Role of salience of bill till payment

The effect of bill is seen in lower water usage after receiving each bill. But people seem to forget about it after making the payment till the next bill.

Table 5

Effect of salience of bill and payment.

Water use	Before-price stage	Priced-stage		
		All days	**Bill to pay days**	**Pay to bill days**
lpcd	114	109	105	110
lpd	319	304	294	306

Note: Effect of salience bill till payment as seen in the water usage in lpcd (liters-per-capita-day) and lpd (liters-per-capita). Priced-stage usage is presented in three ways - all days together, all days split into days from bill communication till payment due date and from payment till next bill communication.

If we look at the response at household level, we again see large divergence in response. One-third of households used more water in bill-to-pay days as compared to pay-to-bill days with an average increase of 11 lpcd (*cf. SI 4.1.6 Salience – bill and payment and Table S18*).

Overall, the summary statistics by various subsets reveals enormous heterogeneity in level of water usage and the response to price-signal, especially based on habits, ownership and prior treatment. Large share of households increased water usage, even amongst high-users and even after a bill communication, suggesting that the water conservation bucket is full of leaks. We now look at the results using four types of effects (Figure 1). Within each effect, we examine potential heterogeneity by subsets of households and periods of time. We triangulate the results of price-effect and bill-effect (i.e., 1 and 4) using two or more tests. In addition, we use intervention time series analysis (effects 2 and 3) to look at price and bill effect in a novel way. We also identify drivers and barriers to conservation in several ways.

Price-effect (aggregate ATE of price)

The results are summarized in Table 6. For details and additional results, also *cf. SI 4.2 Estimated price-effect*.

Aggregate response

Based on the main panel data model, we estimate an ATE of -6.2 lpcd ($p < 0.01$) as the price-effect. The ATE increases marginally to -7 lpcd after the 1st water bill is received ($p<0.05$). When the second water bill is received, which is the also the first bill after reduction of property maintenance rate to take out fixed water charges, the effect is an even larger at -9 lpcd ($p<0.01$). Other variables have expected signs, such as a negative sign for number of residents – larger families are more efficient users of water – and lower use of water in weekends.

Price-effect is also supported in lpd (-14.3 lpd, $p < 0.05$) and master bathroom usage (-4.1 lpd, $p<0.05$). The effect in kitchen & utility area meter has a low significance ($p = 0.12$) though this meter accounts for more than half of water usage. Effect in the common bathroom is not significant (p = 0.17) suggesting a relatively low level of effect on members of the household that use it.

Table 6

Price-effect and heterogeneity of effects.

		Dependent variable (DV) and esti
Heterogeneity	**Subset of data**	**lpcd**
	Aggregate (all households)	**-6.159*** **
lpcd in before-price stage	Above median (high-users)	**-10.62*** **
	Below median (low-users)	-1.432
Habits (water conservation)	High	-4.860
	Low	**-7.281** **
NEP (New Ecological Paradigm)	High	**-8.140** **
	Low	-3.152
Water NEP (Attitude towards water)	High	-6.299
	Low	**-6.092** **
Ownership	Owners	**-5.372** **
	Tenants	-5.585
Non-price treatment's groups	C0 (Control group)	**-10.97***
	T1 (Treated group 1)	**-10.77** **
	T2 (Treated group 2)	0.182
	T3 (Treated group 3)	-7.352
	PI (Post-Intervention)	-0.640

Note: The average treatment effect (ATE) from panel-data regression is presented for aggregate and various subsets of households. Level of significance of ATE: *** p<0.01, ** p<0.05, * p<0.1.

Heterogeneity in price-effect

Panel data tests support that those above median lpcd in the before-price stage reduced very significantly but those below median did not reduce. Using t-test on average lpcd by household by stage, we find similar effect size in high lpcd households (-9.4 lpcd, p = 0.0098) and no effect in low lpcd households. In high lpd households, t-test supports a change of -22 lpd (p = 0.0161) as compared to an overall lpd change of -11.88 (p = 0.0187). The role of level of usage in the before-price period is clear and strong.

We find that households with lower water curtailment habit scores (i.e., weaker curtailment habits) reduced more significantly than those with higher water curtailment habits, both in terms of lpcd and lpd. We further test for role of habit using our LDV model and find similar results. With one-unit increase in the score of habit, the odds of drop in lpcd increases by a factor of 0.4516. Our index of self-reported water habits is thus a useful tool, although our data is based on only one person per household in almost all the cases. However, the difference of price-effects between high and low habit households is not very robust, possibly due to the small sample size and limited habits data per household. Level of habit is a strong predictor of before-price stage usage, especially in treated households.

High-NEP households reduced while low-NEP households hardly reduced. High-NEP households that were above median level of lpcd in before-price stage or were untreated reduced much more than others. In case of Water NEP, while those with lower score reduced more (mirroring lower water habit results), the further subsets show a more nuanced pattern with strong role of baseline usage.

The owners reduce water usage, both in terms of lpcd and lpd, whereas tenants do not reduce. While the estimate is negative for tenants, it is not statistically significant. This result is particularly striking given that owners already use less water in the baseline stage as compared to tenants, by 14 lpcd and 14 lpd.

We find that the effect of price varies by group. The effect is detected in the control group and the treated group T1 that received a mild treatment. T3 has a large effect size but low significance (-7.3 lpcd, p = .109). Other groups have no price-effect.

To further examine heterogeneity of effects, especially at the household level, we turn to time series analysis.

Time series intervention analysis for price-effects

Our analysis based on model (1) provides an estimate of the initial-effect of introduction of water-price. We find that pulse is the best-fitted model at the aggregate level for the community. The estimated initial effect (w) is 4.4 lpcd but it is not statistically significant. None of the four groups support a significant initial-effect of price at 5% level (please refer to table X in SI for the results).

However, beneath this overall lack of initial response, we also observe enormous heterogeneity of response across individual households, not only in terms of the diverse patterns and direction of initial response to introduction of water-price but also in terms of long-term increase or decrease in lpcd.

Initial pattern of impact at household level

Our intervention analysis model (1) classifies the initial response to introduction of price into four types of impacts or patterns – step, build-up, pulse and decay. Step change is the dominant fit (Table 7). Within each of the four patterns, there is either an increase or a decrease in lpcd, revealing another aspect of heterogenous response at household level.

Table 7

Impact of price.

Pattern	Households	Decrease	Increase
1 (Step)	72%	42%	29%
2 (Build-up)	7%	4%	3%
3 (Pulse)	18%	3%	15%
4 (Decay)	3%	1%	2%
Total	100%	51%	49%

Note: Summary of results of household level time series intervention analysis. Patterns 1 and 2 represent persistent change and patterns 3 and 4 represent long-term change. Statistical significance is not included in this summary.

Size of impact (initial-effect and long-term effect)

When we look at the significance of the estimate of initial response to priced-signal, only a quarter of the households reduced lpcd at 5% significance level. The rest either increased lpcd or the response was not statistically significant, supporting divergent responses at household level. The pattern is similar for long-term effect (*cf. SI Table S45*).

Apart from the enormous divergence in response, the size of these effects is also fairly large at an average of 24 to 29 lpcd size in either direction. Thus, the effect of introduction of price-signal is very heterogeneous at the household level.

Bill-effect (role of salience of bill till payment)

We test if the quarterly bill communication acts as a reminder to conserve till the effect tapers off once the payment transaction is complete. Using a panel data model, we find that people do use relatively less water in the days after receiving the bill as compared to other days in the priced-stage (*cf. SI 4.4. Bill-effect or effect of salience of bill*). The effect is even stronger if the first pre-bill period is excluded, signifying that the effect of introduction of price is not as strong as the salience effect of each bill. Second bill also supports bill-effect, despite much smaller number of observations for the regression.

If we look at the data by non-price treatment groups, only the control group supports a bill-effect that is statistically significant. The effect is practically large at -7 lpcd and highly significant ($p<0.01$).

Bill-impact (using time series analysis)

Unlike the introduction of water-price that had no discernible effect at aggregate level, the salience of bill supports an overall effect of -2.5 lpcd ($p < 0.05$). All the group-level results have a negative coefficient and it is also significant in three of the groups – control, T1, and T2 (*cf. SI 4.4.3.Time-series results*).

When we examine household level tests, we find that similar to the introduction of water-price, many households responded to bill by increasing usage (*cf. SI*

Table S50). 48% of the households increased usage with an average of 9 lpcd. The average effect size is a massive 20 lpcd in the 11% of the households with statistically significant increase (p <0.1). The decrease is a large -31 lpcd in the 19% of households with statistically significant decrease (p <0.1). Interestingly, the group of households that increased on receipt of bill had reduced on introduction of water-price (-7 lpcd) and their overall decrease is relatively large (-7 lpcd). The bill seems to have encouraged them to temporarily use more water.

Discussion

Our panel data analysis shows that introducing the price-signal led to an aggregate reduction in water use and that this price effect persisted over the observed period. Time series analysis adds that the introduction of the price-signal had no initial impact on the aggregate, but the bill communications had an impact. These, and other aggregate results are in line with the established wisdom in water conservation research: both price-signal and salience of bill help reduce water demand. However, our analysis framework also provides a peek into previously unmeasured and surprising heterogeneity of effects (viz. around non-price treatment and habits) and its possible determinants. A small subset of households responded with a large change in either direction, but most households responded very little or did not respond to the introduction to price.

Understanding heterogeneity within effects to increase conservation

The aggregate level effects hide the enormous heterogeneity of effects that we detected in the results, which points to a significant potential for improving conservation outcomes. These previously unmeasured heterogeneity of effects can help us understand household behavior in a neglected but important setting (introduction of price-signal) and that in turn can help us design demand management policies towards higher conservation outcomes. In particular, the statistics and tests presented here support that an adverse response to price-signal is possible and that it can be large. In a recent price-change study (Tanishita & Sunaga, 2021), an adverse response was seen and found to be a small fluctuation. A price change does not switch the norms unlike an introduction of price that can lead to more divergent responses. In our study, adverse response is observed in a large subset of households through numerous tests, in both lpcd and lpd measurements, over the entire duration and also after billing events. Further, our dataset includes detailed measurement of the number of residents and its approximate variation by date, that further limits the potential for mistaking noise for signal.

The introduction of price-signal supports a price-effect of 5% reduction in lpcd across all households and 8% reduction in the control group from the prior non-price intervention. This effect size might appear small if we compare it with city-wide rollouts of metering and billing; those have generally produced water savings of at least 10% and often in the 25-30% range (Dalhuisen, Rodenburg, et al., 2003; Herrington, 1999). However, prior interventions in this community had lowered the conservation potential. The community had eliminated use of freshwater in toilet flush by supplying recycled water. They also had campaigns to lower water use, such as through aerators at wash-basins. Garden water use is not a part of the household level meters. Thus, the size of price-effect can be called modest but not large.

A large conservation effect is also about ensuring that low-users continue to remain low-users over time. We see in this quasi-experiment that the group T3 started off at the lowest lpcd among the groups (helped by the most-complete non-price treatment) and also remained the lowest (Table 4). When we further divide each group into high and low water curtailment habits score, in T3 group with high habits reached a very low 85 lpcd (*cf. SI 4.1.7.1. Prior treatment and habits*). This result suggests the need to combine non-price interventions towards high water conservation habits with price-interventions to achieve high and persistent conservation outcomes.

The results imply that alignment of social norms and market norms can lead to higher conservation, as seen in other sectors (Heyman & Ariely, 2004; Keizer & Schultz, 2018). The non-price intervention sought to bring water usage within a difficult and specific per-person goal of 60 lpcd thereby seeking to establish a social-norm among a sub-set of households. The group T3 received this goal and multiple easy tips to form water curtailment habits. The intervention was quite successful in inducing reduction in water usage. Later, when market norm was introduced through start of volumetric billing, the social norm implicitly aligned with a common objective of conservation as seen in group T3 that reduced further. The control group from non-price intervention, that did not receive such an alignment message, used a much higher 130 lpcd in priced-stage (Table 4).

We observe heterogeneous response in terms of self-reported water curtailment habits that suggest a strong potential role of water use habits in maximizing conservation. As hypothesized in water habits literature (Fielding et al., 2012; S. Russell & Fielding, 2010), the households with better water conserving habits used relatively less water before the start of priced-regime (Table 3). We also find that the lower-habit households support a larger price-effect than higher-habit households, though the differences are not very large. This suggests that even high curtailment habits can serve as a barrier to further conservation under market norms.

Our study also reveals the gap between stated attitude towards water and environment and actual behavior. This is in line with prior studies that support that people might state a high pro-water conservation attitude but lack action towards conservation (De Oliver, 1999; S. Russell & Fielding, 2010). The non-price intervention had helped bridge this gap in the treated households (*cf. SI Table S11*). The price-signal further bridged this gap, especially in those with high NEP.

In our study, owners use relatively less water, similar to the finding in other studies that owners invest in water efficiency (Gilg & Barr, 2006; Randolph & Troy, 2008). We also find that owners support a price-effect but tenants do not, except after the 2^{nd} bill. We also see a confirmation of this in bill-effect wherein tenants show a larger effect size as compared to owners. Our results suggest that tenants might benefit from a more frequent bill, especially if the price of water is high-enough to serve as an incentive to conserve. Tenants may require more help to increase conservation, possibly in developing curtailment habits as investments in efficiency may be somewhat less feasible for tenants.

The power of anchoring on behavior is well-known in behavioral sciences though there has been limited application in water conservation (Koop et al., 2019, p. 872). In our study there are two reference points that can serve as an anchor, the community-level median of household water usage (highlighted in quarterly water bill) and a gain or loss amount that is specific to the household. The total quarterly bill for the household implies a net gain or loss as compared to the prior fixed maintenance charge for the household. Note that in our data, the gain-loss boundary of water usage is only slightly lower than median level, i.e., a little more than half the households faced a loss. We see in results that both these reference-points show an effect, especially the median seems to serve as a barrier to conservation. This result is analogous to a recent research on normative messages that found the target, distance and valence of social comparison message combine for the net effect (Bogard et al., 2020). Overall, it suggests that it may be helpful (for better conservation outcomes and for the household bill) to personalize point-of-reference for each household, say based on number of residents and level of usage in the household. Two or three different anchors can be used to make the norm comparison less of a barrier and more meaningful than the prevalent practice of aggregate usage-based comparison regardless of size of the family or current level of usage.

A large percentage difference from a prior value is perceived as a large change with the prior value as the point of reference. In this case, the payment for water bill is made as a part of a larger quarterly bill that includes property maintenance. For example, in Jul-Sep 2018 the average maintenance bill was Indian Rs 26,576 and average water bill was Rs 3,706, i.e., a total of Rs 30,282 of which water bill was only 12%. The property management delivered a printed water bill to highlight the water bill. Nevertheless, the fact that payment transaction was for the total, it could have diminished the effect on water conservation.

In this study, we observed that the reduction in water usage is higher immediately after receiving the bill as compared to days after payment has been made. This is in line with the general findings about payment depreciation, i.e., a bill draws attention till the payment is made (Gourville & Soman, 1998; Gilbert & Zivin, 2014). A more frequent bill could lead to an overall increase in conservation but there are some studies wherein an increase in billing-frequency led to higher usage. This area needs more research, particularly on the level of price, that could explain why seeing a more frequent bill led to higher water use in a North Carolina study (Wichman, 2017), similar to some of the households in our study that increased usage on getting a bill. The start of paying a price for a hitherto free item (or a usage-based price for hitherto flat-fee item) can push a segment of consumers to increase their use, especially if the price is low, since higher average prices are usually associated with lower use (Dalhuisen, J.G., et al., 2003; Grafton et al., 2011).

Heterogeneity in results from time series analysis

Out time series intervention analysis model distinguishes between transient and long-term initial response to the intervention by fitting four different models (Table 7). In our population, 21% of the households fitted best into one of the two transient effect models, i.e., only an initial pulse or blip, or a decay after an initial response. This transient response was largely an increase (17%). Most households (72%) fitted into a step-change model, which were somewhat equally split between increase and decrease. Only 7% fitted into the build-up model wherein their response stabilized over time to a new level (3% fitted into increase and 4% into decrease). Overall, half (49%) of the households responded with an initial increase in usage.

If we look at statistical significance of the estimate, only a quarter of the households initially reduced usage on introduction of price-signal; all other households either did not respond or increased usage. Actual daily water usage data is even more skewed; nearly half the households increased usage and less than 12% contributed as much as the entire reduction in daily water use. When we combine this result with presence of a bill-effect, the importance of a more frequent bill for more days of lower-use becomes evident.

The large heterogeneity of response in all the effects and summary statistics suggests that many households responded to the initial price-signal by switching from a social norm to a market norm. Even though they started to face a marginal cost of water use, they seem to have chosen to pay more. A better communication in place of a median, or a simultaneous non-price intervention, might have helped in better alignment of norms leading to reduced adverse response.

Contribution to PES (Payment for Environmental Services) literature

The findings from our quasi-experiment add a new dimension to the ongoing debate on whether to employ PES or not. We suggest that not only the context of use of PES is crucial, as argued in Conservation Letters (Muradian et al., 2013; Wunder, 2013), it is also important to recognize the heterogeneous response to interventions within the same context. People respond differently based on their characteristics, such as habits and attitudes, and their prior state, i.e., their level of use in the pre-intervention stage and the treatment that they received earlier. A recognition of heterogeneity in subjected population and the expected divergence in effects is central to maximize the impact from introduction of price-signal.

The conceptual framework used in PES recognizes three potential long-term outcomes from introduction of price: performance below pre-PES level, same as pre-PES level, and above pre-PES level (Ezzine-de-Blas et al., 2019, fig. 1). These are equivalent to decrease, no-change and increase in water use, respectively. However, While Ezzine-de-Blas et al. discuss only a favorable short-term response, both our results support that the short-term response can also be adverse, leading to an improved characterization of possible responses.

Integration of social sustainability into price-policy

An introduction of price for water can also lead to hardship for the economically weaker segment of consumers, leading to adverse and avoidable consequences. Out study does not provide much insight into this issue; though we have some variation in income across households, it is a fairly homogenous community. We also do not detect much significance of level of income within this population (*cf. SI Table S37*).

In the general literature, this issue has been well recognized in the water sector in the developing countries (Whittington, 1992, 2003). More recently, this has also been witnessed in some rich countries, e.g., in France and Sweden (Barraqué, 2011; Mangold et al., 2014). These studies reveal that while the price-policy maybe an overall success in terms of water conservation objectives, additional measurements are necessary to ascertain its success on the social dimension in subsets of population. It is conceivable to contain adverse social consequences, and possibly even eliminate it, through suitable integration of parameters of social sustainability into the design of water tariff (Cook & Whittington, 2020).

Gaps and limitations

In an ideal experiment to study the effect of a treatment, there would be a control group to compare with the treatment group, apart from low-granularity (e.g., daily) measurement of resource usage for a long-period (two years or more). Such a perfect setting, ideally based on random allocation of price-treatment, is not only unlikely to be created, it may also be unethical or even illegal. Some randomly selected households cannot be asked to pay a usage-based price while others in the same population pay a fixed price, regardless of usage. This makes our quasi-experiment the near-ideal setting. Nevertheless, it would have been even more revealing if the population were much larger. With research funding, it should be easily possible to delay the start of water-pricing after installation of meters. Such funding is entirely in line with the earlier calls to invest in observations towards social science of water systems, though this crucial aspect was missing in earlier water research recommendations (Braden et al., 2009; National Research Council, 2001).

Advances in information and communication technologies have led to investments in detailed measurement and feedback on water use through use smart metering (Cominola et al., 2019). While this has been helpful in understanding of human behavior, there does not seem to be any effort in applying these investments to understand water use behavior on introduction of market norms, or pre-market behavior. Such research would help further improve our understanding of heterogenous role of price-signal.

Conclusion

In this study, we examined three main questions to maximize water conservation. One, what is the aggregate response to the introduction of price-signal (price-effect) and the response on receipt of bill (bill-effect). Two, what is the heterogeneity of these two effects in various subsets of households and time. Three, what factors explain the differences in response between aggregate and subsets. Our results support a role of price-signal, water curtailment habits, prior usage level, ownership of residence, number of residents, prior-intervention, and the bill-to-pay period on water conservation outcomes.

This study contributes to the understanding of heterogeneous response to price interventions and the explanatory factors underlying it. This is a subject of debate with arguments on use of price (Grafton et al., 2011; Wunder, 2013) and some concerns about use of price (Muradian et al., 2013; Pellerano et al., 2017). The setting in our quasi-experiment allowed us to gain new insights about some of the key factors that can explain the puzzling heterogeneity of response that makes the water conservation bucket full of leaks. These insights can not only steer us towards more specific research directions but also in implementations to achieve higher level of conservation. The potential for adverse response to price-signal has existed in behavioral theories and it has been confirmed in this study by measuring it over a long-duration and through multiple-measurements at household level.

This study helps us recognize that the effect of policy interventions is an interplay between various factors that can act in opposite direction leading to adverse response at household level. For instance, a family of residents that learns high water curtailment habits through a non-price intervention might reduce a lot in one period to reach a very low lpcd but then they become less likely to further decrease lpcd on introduction of price-signal. Total effect depends on accumulation of changes, not only across households but also over time-periods. Thus, the ambitious overarching question for further research could be to establish what distinguishes water use reduction outcomes from water use increase outcomes, in each household and each time-period, and by using these insights, can policy makers and property managers intervene better to guide behavior towards much higher water conservation?

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