Pricing Urban Water: Rate Structures and Scarcity Rents Under Supply Uncertainty

Connor Neff
University of Tennessee Knoxville
connor.neff@utk.edu

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Abstract

Municipal water utilities are mandated to recover costs, balance equity concerns, and send conservation signals. Yet the degree to which observed prices reflect the scarcity value of water remains largely unexplored. This paper develops a stochastic dynamic program in which the optimal two-sector price decomposes into a Ramsey markup, a scarcity rent on the water stock, and sector-specific marginal cost. Residential and non-residential demand elasticities of -0.59 and -0.82, respectively, are estimated from a novel panel of 194 Arizona water utilities (2014–2019). Simulated model-implied optimal prices show that increasing block rate (IBR) utilities price closer to the dynamic optimum than uniform-rate utilities. The welfare loss from suboptimal pricing is \$11 to \$26 per customer greater under uniform rates than IBR, and uniform structures undervalue the water stock by 20% relative to IBR. IBRs more fully capture the scarcity rent of water than uniform pricing, and this advantage widens as supply conditions tighten.

JEL codes: D12; L95; Q25
Key Words: water pricing, natural capital, natural monopolies, rate structures, scarcity rent

1 Introduction

Water supplies around the world are increasingly strained by intensifying droughts driven by climate change. Many urban water users in the southwestern United States rely on purchased water from a shared supply whose availability fluctuates with drought conditions. This region is more exposed to shortages than ever as it experiences historically exceptional drought severity (Williams et al., 2022). Water utilities and regulators must adequately design and set rates to incorporate the scarcity and uncertainty of supplies to maximize social benefit.

Standard results from dynamic resource economics imply that the efficient price water utilities charge should embed a time-varying scarcity rent when utilizing an uncertain supply source. Chronic underpricing of a resource encourages excess consumption, starves utilities of revenue for infrastructure investment, and generates welfare losses that compound as hydrological conditions deteriorate (McRae, 2015). Yet many U.S. municipal water utilities charge prices that fall below average operating costs, let alone the long-run marginal cost inclusive of the scarcity rent (Hanemann, 1998; Timmins, 2002b; Olmstead, 2010; Wichman, 2024). Water utilities are often constrained by political pressures to balance equity and affordability concerns with budget management and conservation signals. Utility managers together with regulators often employ nonlinear rate structures to balance these political, environmental, and budgetary pressures. The financial and distributional consequences of these pricing decisions are well-documented,[1] yet the natural resource management implications are much less understood. In water-abundant regions, where many studies of pricing focus, underpricing the scarcity rent element is much less of a concern as compared to water-scarce regions like the western United States.

In this paper, I study the extent to which scarcity rents have been incorporated into water prices of the recent past and the implications rate structures have on natural resource value and social welfare. I first develop a dynamic Ramsey pricing model for a two-sector (residential and non-residential) municipal water utility facing stochastic supply shocks. I extend Sağlam (2019) by centering the manager's problem on the decision to purchase and bank external water supplies as insurance against future shortages, rather than relying solely on price adjustments to ration demand. The model yields a clean decomposition of the optimal price for each sector: marginal cost

[1] As noted in Wichman (2024), these rate structures discount volumetric prices for low levels of consumption (Olmstead et al., 2007; Szabó, 2015; Wang and Wolak, 2022; Allaire and Dinar, 2022), may generate allocative inefficiencies (Borenstein, 2012, 2016; Borenstein and Davis, 2012), require subsidization from alternative municipal revenue sources (Timmins, 2002a; Renzetti, 1999), and ineffectively redistribute income (Levinson and Silva, 2022; Wietelman et al., 2025).

plus a Ramsey markup plus the scarcity rent. The scarcity rent evolves over time and is endogenous to current storage, carryover revenue, and the distribution of the supply shock. I apply the model to Arizona and estimate parameters using a novel panel of 194 water utilities over 2014–2019, assembled from utility-level rate schedules, supply and withdrawal records, financial filings, and purchased delivery data to provide evidence that observed prices deviate from optimal. Finally, I simulate the optimal pricing policy for different utilities to investigate the magnitude of pricing inefficiencies by rate structure.

The divergence between observed and efficient water prices is well-documented, but the existing literature benchmarks efficiency against average cost recovery rather than the socially optimal price that incorporates a forward-looking scarcity rent. McRae (2015) shows that politically constrained utilities are trapped in an equilibrium where rate increases are blocked by consumer-voters who do not internalize the resource cost. Wichman (2024) documents widespread cost-recovery failures across municipal utilities in the southeastern U.S. where water resources are not scarce. To my knowledge, no study asks whether increasing block rate (IBR) versus uniform rate structures differ in their capacity to embed the scarcity rent, nor derives the efficient benchmark from a structural dynamic model. I fill this gap by calibrating a stochastic dynamic program to utility-level data and testing how rate structure type affects alignment between observed and optimal prices over simulated resource scarcity scenarios.

I make three contributions. First, I provide simulation evidence that IBR structures align observed prices more closely with the dynamic Ramsey optimum than uniform rate structures, and that this advantage is larger under more scarce water scenarios. Municipal water ratemaking requires formal regulatory approval and generates political friction, so observed rates often lag optimal prices by five years or more (Hanemann, 1998; McRae, 2015). A flat rate, once set, cannot differentiate scarcity signals across consumption levels between rate reviews; an IBR's tiered schedule embeds a price gradient that can partially approximate the scarcity rent even when the overall rate level cannot be adjusted. I find that in the recent past, IBR utilities price residential water about 20-percent closer to the model-implied optimum than uniform-rate utilities. Second, I show that the welfare advantage of IBR structures over uniform rates widens as shortage severity increases. I simulate five-year paths under mild and severe supply shock scenarios and find that welfare gains for utilities with uniform rate structures moving to optimal prices are much larger than those operating at increasing block rates. Third, I provide estimates of price elasticity of water demand for both residential and non-residential sectors. I estimate both from the same panel using a cross-market instrument in the style of Hausman et al. (1994) and Nevo (2001) for the endogenous marginal price.[2] The empirical water demand literature has focused almost exclusively on the residential sector (Dalhuisen et al., 2003; Olmstead, 2010), leaving non-residential demand, which accounts for a substantial share of total municipal withdrawals, largely unexamined at this scale. I show that non-residential water demand is more price-elastic than residential. Utilizing a single elasticity from residential demand would result in smaller demand reductions for increased prices and understate estimates of welfare changes.

The empirical contribution rests on a data set assembled from multiple public sources and those requiring public records requests to access. I combine utility-level rate schedules from University of North Carolina-Chapel Hill's Environmental Finance Center for four survey years (2014, 2015, 2017, 2019), annual supply and withdrawal quantities by source type from the Arizona Department of Water Resources, financial data from Arizona Corporation Commission annual reports, and Central Arizona Project (CAP) delivery records by entity and contract tier. The resulting panel covers 194 utilities supplying approximately 5.6 million of Arizona's 7.6 million residents. The CAP shortage mechanism translates Lake Mead elevations directly into delivery reductions by contract type and provides the empirical analog to the supply shock in the model.

I estimate residential price elasticity of demand at $-.51$ to $-.59$ using an instrumental variables strategy that instruments for the marginal price with the average price charged by neighboring utilities in the same county, lagged one period. This strategy follows from modern applications and recent discussion on the validity of Hausman instruments (Autor et al., 2013; Berry and Haile, 2021; MacKay and Miller, 2025) and is in a similar range of recent water demand elasticity estimates (Mansur and Olmstead, 2012; Wichman, 2014; Szabó, 2015; Brent and Ward, 2019; Wichman, 2024; Wietelman et al., 2025). Commercial demand elasticity is estimated at $-.78$ to $-.83$ using the same methodology, which is the first study that estimates urban non-residential water demand at scale. This range is on the more elastic end of residential water demand estimates but in line with recent evidence from Burlig et al. (2021) on agricultural water demand estimates.

Following Wichman (2024), I estimate marginal costs and recover utility-year estimates that reflect differences in regulation and use of external purchased water. I combine these marginal cost estimates with the full data to recover optimal prices using the model for each utility-year combination. I find that utilities with increasing block rates price water significantly closer to the

[2] Berry and Haile (2021) and MacKay and Miller (2025) detail the conditions which must hold for this instrument to identify the price parameter. The key condition is that the demand shock in the focal market is mean-independent of the price in the other market conditional on observables.

model-derived optimal regardless of CAP water use. The median IBR utility prices residential water approximately 43-cents closer per thousand-gallons (kgal) to the model-implied optimal prices compared to the median uniform rate utility. I further explore this result by simulating five years of the model for all CAP water purchasing utilities in my sample and show that uniform rate utilities see much larger welfare gains from moving to optimal prices than IBR utilities. Welfare change is measured as the difference in value functions evaluated at status quo prices and those from the dynamic optimal where optimal prices are chosen to maximize consumer surplus, utility net revenues, and stock of water for future use. Over 500 simulations of 5-year paths, the median IBR utility sees no welfare gain or loss switching to optimal prices, whereas the median uniform rate utility sees welfare gains of \$11.60 per customer under severe water shortage scenarios. Under mild shortage scenarios, the median IBR utility improves welfare by \$11 per customer per year and the median uniform rate utility by \$37.6 per customer from optimal pricing. The larger welfare gains under mild shortage scenarios illustrate how a majority of the benefits from optimal pricing accumulate in abundant periods, allowing the water manager to expand stocks for future periods of scarcity.

I build most directly on the stochastic dynamic programming literature for water resource pricing. Moncur and Pollock (1988) develop an early valuation and pricing model for urban water scarcity in which the efficient price incorporates a rent reflecting the opportunity cost of current consumption. Sağlam (2019) formalizes this into a stochastic dynamic program for a water utility facing uncertain supply, characterizing optimal prices as a combination of the inverse-elasticity Ramsey markup, a scarcity rent of the water stock, and sector-specific marginal costs. Tsur (2020) derives optimal groundwater pricing when extraction costs depend on the water table, and Chu and Grafton (2021) incorporate supply uncertainty into a risk-adjusted user cost. I also connect this pricing literature to the natural capital accounting framework of Fenichel and Abbott (2014) and Fenichel et al. (2016), who show that the scarcity rent of a resource stock is the theoretically correct measure of its natural capital price and demonstrate recovery of stock prices from observed behavior for groundwater. I provide the first empirical implementation of a Saglam-style stochastic dynamic program using utility-level data and connect the recovered scarcity rent directly to the natural capital literature, situating the rate structure comparison within a broader accounting of water as a stock resource. Under greater supply uncertainty, scarcity rents rise slightly due to utilities having less access to purchase and store water for future periods even if they have revenue surplus.[3]

A large empirical literature studies demand effects and equity implications of nonlinear water pricing but takes the rate structure as given rather than asking how closely it tracks efficient prices. Wang and Wolak (2022) characterize the trade-off between revenue recovery and conservation in nonlinear price schedule design, showing that optimal schedules depend critically on elasticity heterogeneity across usage tiers. With greater demand elasticity among high-use non-residential customers as estimated in this paper, it is unclear whether IBR or uniform rate structures better approximate the conservation signal. Mansur and Olmstead (2012) shows that replacing quantity rationing with market-clearing prices raises welfare substantially. I depart from this literature by asking not how demand responds to observed rate structures, but how well observed rate designs approximate the optimal price which incorporates the scarcity rent. This question is unanswered and connects directly to whether rate design captures the natural capital value of the water stock as supply conditions change between rate reviews.

The remainder of this paper is organized as follows. Section 2 presents the dynamic pricing model and derives optimal prices analytically. Section 3 provides institutional background on the Central Arizona Project and the shortage declaration mechanism. Section 4 describes the data. Section 5 estimates residential and non-residential demand. Section 6 estimates marginal costs. Section 7 presents results comparing observed and optimal prices across rate structures and quantifies the welfare loss from suboptimal pricing. Section 8 concludes.

2 Model

In this model, a benevolent water manager chooses prices and quantity of water purchased to maximize the net present value of customer consumer surplus. Customers fall into one of two user groups: residential and non-residential. The manager is constrained by a stochastic resource constraint and a budget constraint requiring cost recovery.

[3] Abbott et al. (2026) show that stochasticity does not change scarcity rents significantly unless nonconvexities in the resource dynamics are present.

2.1 Water Management Problem

The water manager's optimization problem can be written recursively as follows:

$$V(w,b) = \max_{p_1,p_2,x(\theta)} \mathbb{E}_\theta \Big[\sum_{i=1}^{2} CS_i(p_i) + \beta V(w'(\theta), b'(\theta)) \Big] \tag{1}$$

$$s.t. \quad w'(\theta) = w + w_f + x(\theta) - \sum_{i=1}^{2} q_i(p_i); \quad \forall\theta, \tag{2}$$

$$b'(\theta) = (p_1 - c_1)q_1(p_1) + (p_2 - c_2)q_2(p_2) + Rb - \tau - p_x x(\theta); \quad \forall\theta, \tag{3}$$

$$x(\theta) \leq \bar{x}(\theta), \tag{4}$$

$$w \geq 0, \tag{5}$$

where all prices and quantities are non-negative with the exception of the carryover stock, $w'(\theta)$. Carryover stock may be negative representing a withdrawal from the water manager's total stock. However, the amount of water in storage w must be non-negative. The discount factor is denoted β, and $CS_i(p_i)$ represents the consumer surplus for each user group in $i = 1, 2$.

The expectation operator $\mathbb{E}_\theta(\cdot)$ is over the supply shock θ, which is drawn independently each period from a known distribution. The control variables for the manager's stochastic dynamic programming (SDP) problem are the prices for each user sector $\{p_1, p_2\}$, the quantity of purchased water $\{x(\theta) \geq 0\}$, and the carryover stock and revenue $\{w'(\theta), b'(\theta)\}$. After solving for prices and purchased water, the carryover stock and revenue can be computed from the constraints.

The third constraint represents the maximum amount of water available for purchase in this period, which is constrained by the current-period supply shock θ. The shock θ is drawn independently each period from a Beta distribution on the interval $[0, 1]$.

The maximum water available for purchase is therefore:

$$\bar{x}(\theta) = \bar{x} \cdot \theta, \tag{6}$$

where $\bar{x}$ is the contractual maximum amount the water manager is allowed to purchase.

Let $\lambda(\theta)$ and $\mu(\theta)$ be the Lagrange multipliers on the resource constraint (2) and the revenue constraint (3), respectively. Also, let $\eta(\theta)$ denote the Lagrange multiplier for the purchased water constraint (4). Equation 5 is a non-negativity constraint imposed on the amount of water in storage.

2.2 Timing

I consider residential (sector 1) and non-residential (sector 2). Let θ denote a supply-side stochastic shock to the model. I denote sectoral demand by sector i as $q_i(p_i)$.

At the beginning of the period, the water manager observes the carryover stock (w). Before the supply shock is realized, the manager sets prices (p_1, p_2). Sectoral prices are determined ex ante and do not depend on the current-period supply shock. Once the shock is observed the manager can decide to augment the existing stock by purchasing water (x) at unit cost (p_x). At the end of the period the remaining stock $(w'(\theta))$ is saved for the next period.

2.3 Resource Constraint

The dynamic resource constraint for the intertemporal resource allocation is:

$$w'(\theta) + q_1(p_1) + q_2(p_2) \leq w + w_f + x(\theta); \quad \forall\theta, \tag{7}$$

where the left-hand side (LHS) is the sum of savings and total withdrawals. Specifically, $w'(\theta)$ is the remaining stock at the end of the period that is saved for next period and $q_1(p_1)$ and $q_2(p_2)$ are sectoral demands. In the optimization problem this resource constraint generates Lagrange multiplier λ which is the shadow value of the resource and when scaled by the resource constraint Lagrange multiplier μ generates the scarcity rent. This scarcity rent is the main measure of natural resource value evaluated throughout the results section of this paper.

The right-hand side (RHS) is the total supply. This is the sum of savings from last period (w), fixed water stock (w_f)[4], and the additional purchased water $(x(\theta))$. I assume that the water manager can only purchase this water and not sell it, therefore $(x(\theta) \geq 0)$.

A shortage occurs in a period when aggregate demand exceeds the amount of fixed water supply available plus available water for purchase. For a given supply shock θ:

$$q_1(p_1) + q_2(p_2) > w_f + x(\theta). \tag{8}$$

A shortage may occur due to high consumption or low supply resulting from an adverse supply

[4]This is water that the water manager has a fixed right to. This includes groundwater rights and surface water rights, which I assume are fixed.

shock. The water manager can respond to the shortage by drawing down its savings or by pricing water higher to signal scarcity to users.

2.4 Budget Constraint

The water manager is bound by a dynamic revenue constraint which requires cost recovery. Let $[c_1, c_2]$ denote constant marginal costs for the two sectors and τ represent the fixed cost of production for all users. Following Sağlam (2019), I assume marginal costs may differ between sectors due to differences in production costs or accessibility[5]. The water manager's budget constraint is:

$$b'(\theta) + p_x x(\theta) \leq (p_1 - c_1)q_1(p_1) + (p_2 - c_2)q_2(p_2) + Rb - \tau, \tag{9}$$

where b and $b'(\theta)$ denote the carryover revenue (in the form of bonds) from last period and this period, respectively, and R is the fixed gross rate of return on bonds. The bond savings $b'(\theta)$ are non-negative, meaning the water manager cannot finance losses by issuing bonds.

Equation 9 is consistent with cost recovery, as the revenue must cover cost throughout the periods.

2.5 Optimal Policy Functions

The optimal policy functions follow from the first-order (FOC) and envelope (EC) conditions of the dynamic program (1)–(5). Because sectoral prices (p_1, p_2) are set ex ante before the supply shock θ is realized while the CAP purchase $x(\theta)$ is chosen ex post after observing θ, the analysis has a natural two-stage structure. I first characterize the intertemporal Euler conditions governing the carryover stock $w'(\theta)$ and revenue $b'(\theta)$, then derive the optimal pricing rule, which is the central result.

[5]Production costs may include differing water quality required by user groups. Accessibility costs such as transfer costs may differ by user groups. Empirically, I use marginal costs that are the same across user-groups within a utility.

2.5.1 Optimal Carryover Stock and Revenue

Taking the first-order and envelope conditions of the Bellman equation with respect to $w'(\theta)$ and w:

$$\text{FOC:} \quad \frac{\beta\,\partial V(w'(\theta),\, b'(\theta))}{\partial w'} = \lambda(\theta), \tag{10}$$

$$\text{EC:} \quad \frac{\partial V(w,\, b)}{\partial w} = \mathbb{E}_\theta[\lambda(\theta)]\,. \tag{11}$$

Iterating equation (11) forward one period and substituting (10) yields the Euler equation for the carryover water stock:

$$\lambda(\theta) = \beta\,\mathbb{E}_{\theta'}\left[\lambda'(\theta')\right]. \tag{12}$$

Equation (12) equates the current shadow value of one unit of water stock with the discounted expected shadow value tomorrow. When storage is low and $\lambda(\theta)$ is high, the value function is steeply increasing in w; the utility responds by raising prices to reduce current withdrawals and preserve stock for future periods.

The analogous conditions for carryover revenue $b'(\theta)$ and b yield the Euler equation for revenue:

$$\text{FOC:} \quad \frac{\beta\,\partial V(w'(\theta),\, b'(\theta))}{\partial b'} = \mu(\theta), \tag{13}$$

$$\text{EC:} \quad \frac{\partial V(w,\, b)}{\partial b} = R\,\mathbb{E}_\theta[\mu(\theta)]\,, \tag{14}$$

which gives:

$$\mu(\theta) = \beta R\,\mathbb{E}_{\theta'}\left[\mu'(\theta')\right]. \tag{15}$$

The shadow value of a dollar of carryover revenue today equals the discounted expected shadow value next period scaled by the gross bond return R. The utility saves budget surplus when high prices generate revenue that can finance CAP purchases or underwrite below-cost pricing in future periods of abundance, following Sağlam (2019).

2.5.2 Optimal Sectoral Prices

Sectoral prices are the primary policy instrument and the focus of the empirical analysis. Taking the derivative of the Bellman objective (1) with respect to p_i, and using the fact that $q_i(p_i)$ does not depend on θ since prices are set ex ante, the first-order condition for sector i is:

$$0 = \frac{\partial CS_i}{\partial p_i} + \mathbb{E}_\theta \left[-\lambda(\theta) \frac{\partial q_i}{\partial p_i} + \mu(\theta) \left((p_i - c_i) \frac{\partial q_i}{\partial p_i} + q_i(p_i) \right) \right]. \tag{16}$$

Applying Roy's identity, $\partial CS_i / \partial p_i = -q_i(p_i)$, and defining $\bar{\lambda} \equiv \mathbb{E}_\theta[\lambda(\theta)]$ and $\bar{\mu} \equiv \mathbb{E}_\theta[\mu(\theta)]$ as the expected shadow prices on the resource and revenue constraints, respectively, equation (16) simplifies to:

$$(\bar{\mu} - 1)\, q_i(p_i) + \left(\bar{\mu}(p_i - c_i) - \bar{\lambda} \right) \frac{\partial q_i}{\partial p_i} = 0. \tag{17}$$

Because demand $q_i(p_i)$ and its derivative $\partial q_i / \partial p_i$ are non-stochastic—a consequence of prices being set before θ is observed—the expectations in (16) reduce to the scalar multipliers $\bar{\lambda}$ and $\bar{\mu}$. Solving (17) for p_i yields the following result.

The optimal volumetric price for sector $i \in \{1, 2\}$ satisfies:

$$p_i = \underbrace{\left(\frac{\bar{\mu} - 1}{\bar{\mu}} \right) \left(\frac{-q_i(p_i)}{\partial q_i / \partial p_i} \right)}_{\text{Ramsey markup}} + \underbrace{\frac{\bar{\lambda}}{\bar{\mu}}}_{\text{scarcity rent}} + \underbrace{c_i}_{\text{marginal cost}}, \tag{18}$$

where $\bar{\lambda} = \mathbb{E}_\theta[\lambda(\theta)]$ and $\bar{\mu} = \mathbb{E}_\theta[\mu(\theta)]$ are the expected Lagrange multipliers on the resource and revenue constraints.

The optimal price decomposes into three additive components. The first term is the Ramsey markup: the inverse-elasticity rule scaled by $(\bar{\mu} - 1)/\bar{\mu}$, which measures the tightness of the revenue constraint. A sector with less elastic demand bears a proportionally larger markup, recovering fixed costs τ while minimizing aggregate welfare loss. The second term, $\bar{\lambda}/\bar{\mu}$, is the scarcity rent: the expected shadow value of the water stock normalized by the shadow value of revenue. This is the forward-looking opportunity cost of drawing down one unit of storage—the same object identified as the user cost of a scarce resource by Moncur and Pollock (1988) and as the natural capital value of a stock by Fenichel and Abbott (2014). The scarcity rent is endogenous to the state (w, b) and the distribution of θ: it rises when storage is low relative to expected demand or when the supply shock tightens the CAP constraint, embedding a conservation signal into the optimal price.

The third term is the sector-specific marginal cost of supply.

Two limiting cases clarify the structure of (18). When the revenue constraint is slack ($\bar{\mu} \to 1$), the Ramsey markup vanishes and the rule collapses to $p_i = \bar{\lambda}/\bar{\mu} + c_i$: full marginal user cost pricing, the efficient benchmark from dynamic resource economics. When storage is abundant and no shortage threatens ($\bar{\lambda} \to 0$), the scarcity rent disappears and the rule reduces to the static Ramsey benchmark, recovering fixed costs through inverse-elasticity markups alone. The empirically relevant case for Arizona utilities combines both: revenue constraints are real and the CAP shortage mechanism makes supply uncertainty salient, so both components should be present in observed prices to achieve efficiency.

Because both sectors share the same scarcity rent $\bar{\lambda}/\bar{\mu}$, prices differ across sectors only through their Ramsey markups, which depend on sector-specific demand elasticities. With $|\hat{\varepsilon}_2| = 0.82 > |\hat{\varepsilon}_1| = 0.59$, non-residential demand is more elastic than residential demand in my estimates, so the residential sector receives the larger Ramsey markup in the optimal solution. The scarcity rent, however, is the same for both sectors—reflecting the fact that a unit of water drawn from storage by any user group carries the same opportunity cost to the utility.

2.5.3 Demand for External Water

The dynamic program is linear in the CAP purchase $x(\theta)$ for each realization of θ. Taking the first-order condition with respect to $x(\theta)$:

$$\lambda(\theta) - p_x\, \mu(\theta) = \eta(\theta) \geq 0, \tag{19}$$

with complementary slackness $\eta(\theta)(\bar{x}(\theta) - x(\theta)) = 0$. Equation (19) states that the utility purchases CAP water when the shadow value of an additional unit, $\lambda(\theta)$, is at least as large as its effective cost $p_x\, \mu(\theta)$. When $\lambda(\theta) < p_x\, \mu(\theta)$, the external source is too costly relative to the value of additional storage and $x(\theta) = 0$; when the CAP constraint binds, $\eta(\theta) > 0$ and $x(\theta) = \bar{x}(\theta) = \bar{x} \cdot \theta$.

3 Institutional Background

Arizona municipal water utilities draw from three primary supply sources: surface water rights governed by prior appropriation doctrine, groundwater extracted from local aquifers, and purchased Colorado River water delivered through the Central Arizona Project (CAP). Groundwater and surface water rights are held long term and typically are not subject to variation year-to-year. Unused water from either source does not roll over to the following year. Excess water from any source may be stored through the Arizona Water Banking Authority (AWBA). The relative weight of each source varies considerably across the state, with CAP-dependent utilities concentrated in the Phoenix and Tucson metropolitan corridors and groundwater-reliant utilities predominating in rural areas.

The regulatory environment divides the state into Active Management Areas (AMAs) and non-AMA regions. The five AMAs (Phoenix, Tucson, Pinal, Prescott, and Santa Cruz) were established under Arizona's 1980 Groundwater Management Act in response to severe aquifer overdraft, and utilities operating within them are subject to mandatory conservation programs and a 100-year assured water supply requirement administered by the Arizona Department of Water Resources (ADWR). Non-AMA utilities face no equivalent supply adequacy standard and are regulated primarily through the Arizona Corporation Commission (ACC) on financial and service-quality grounds, with groundwater extraction constrained only by well permitting and local basin conditions.

The Central Arizona Project (CAP) is a 336-mile aqueduct system that diverts Colorado River water from Lake Havasu eastward and southward to serve the Phoenix and Tucson metropolitan areas (see Figure 5 in the appendix), with first water deliveries in 1985 and the backbone aqueduct substantially complete by 1993 (Hanemann, 2002). The Central Arizona Water Conservation District (CAWCD) holds Arizona's Colorado River allotment and delivers water to end-users through long-term subcontracts; the 52 current municipal and industrial (M&I) subcontractors collectively hold entitlements totaling approximately 620,000 acre-feet per year. In a normal year CAP delivers approximately 1.5 million acre-feet across all user classes, accounting for around 35 percent of Arizona's total water use (Central Arizona Project, 2024). CAP water is distributed by a strict priority hierarchy: tribal water holds the highest priority, followed by M&I subcontract water, then non-Indian agricultural (NIA) water, and residual excess water at the lowest tier. The amount of CAP's allotment is determined by the level of Lake Mead pool elevation. The lake's elevation has been steadily declining for the last 25 years, reaching historically low levels near the end of 2025 as shown in Figure 1.

The shortage mechanism translates Lake Mead reservoir elevations directly into reductions in CAP deliveries to Arizona. Under the Bureau of Reclamation's 2007 Interim Guidelines, a Tier 1

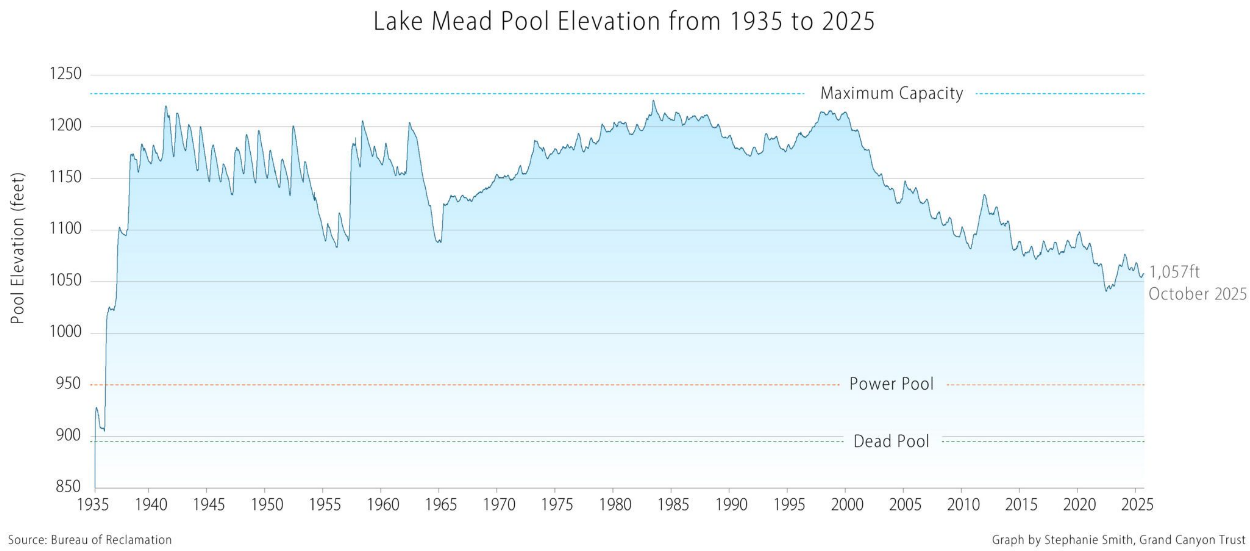


Figure 1: Lake Mead Pool Elevation, 1935–2025

Notes: Monthly pool elevation in feet above sea level, January 1935 through October 2025. The reservoir stood at 1,057 feet in October 2025, its lowest sustained level in the recorded record. Dashed reference lines mark maximum storage capacity (≈1,229 ft), power pool (≈950 ft), and dead pool (≈895 ft). Source: U.S. Bureau of Reclamation; figure by Stephanie Smith, Grand Canyon Trust.

shortage is triggered when Lake Mead is projected to fall below 1,075 feet reducing Arizona's CAP allocation by 512,000 acre-feet annually; Tier 2 and Tier 3 conditions cut deliveries by up to 720,000 acre-feet from the full entitlement (U.S. Bureau of Reclamation, 2007). Because cuts fall first on NIA and excess water pools, M&I subcontract holders retain most of their deliveries under moderate shortage conditions, though severe shortages affect all user classes. In August 2021, the Bureau of Reclamation declared the first Tier 1 shortage for calendar year 2022, and conditions worsened to Tier 2a in 2023. Figure 2 shows that Lake Mead elevations approach Tier 3 in late-2027 under both most probable and minimum probable scenarios. Droughts induced by climate change indicate that Colorado River rationing may become more frequent and intense. This uncertainty in supply is captured by the supply shock in the model.

To buffer against shortage-driven delivery reductions, Arizona utilities and the Arizona Water Banking Authority (AWBA) bank surplus CAP water underground during years of abundant supply. When deliveries exceed immediate demand, utilities recharge water into permitted underground storage facilities and ADWR tracks the resulting Long-Term Storage Credits (LTSCs), which can be withdrawn in future periods. Through 2024, the AWBA had accumulated approximately 4.4 million acre-feet of LTSCs, with roughly 2.3 million acre-feet designated specifically to firm M&I subcontract supplies during shortage events (Arizona Water Banking Authority, 2024).

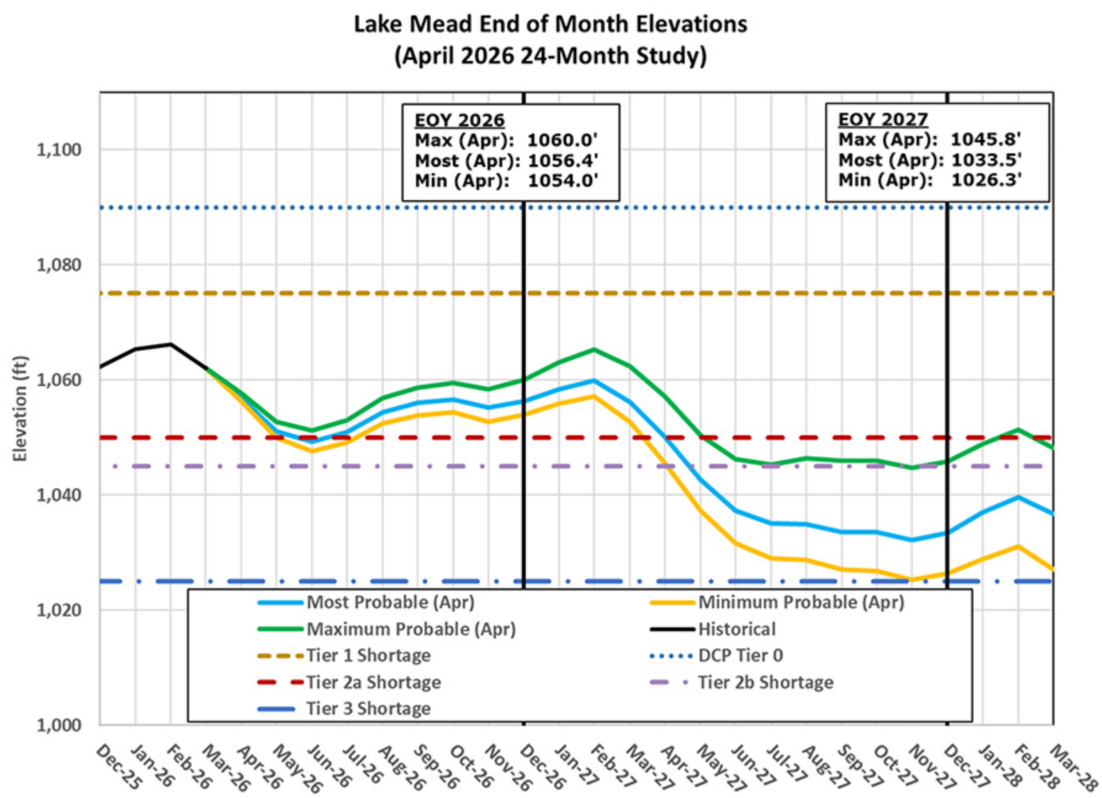


Figure 2: Lake Mead End-of-Month Elevation Projections, 2026–2028

Notes: Bureau of Reclamation April 2026 24-Month Study projections of Lake Mead end-of-month pool elevation through March 2028. Lines show most probable, maximum probable, and minimum probable outcomes. Horizontal dashed lines mark shortage tier thresholds: Tier 1 (1,075 ft), Tier 2a (1,050 ft), Tier 2b (1,045 ft), and Tier 3 (1,025 ft). Under the most probable scenario, end-of-year elevations are projected at 1,056 ft in 2026 and 1,034 ft in 2027, implying continued Tier 2a shortage conditions. Source: U.S. Bureau of Reclamation.

Utilities can also hold storage credits directly and draw them down when CAP deliveries fall short, converting a stochastic flow entitlement into a more reliable supply through active inventory management. This arrangement is the empirical analog to the water stock in the model, generating the intertemporal trade-off at the center of the Ramsey pricing problem.

4 Data

I combine data on rates, supply quantities, withdrawal quantities, revenues, and expenditures from disparate public data sources and public records requests to assemble a four-year panel for 194 utilities in Arizona.

4.1 Water Rates Data

I retrieve Arizona water rates data from UNC-Chapel Hill's Environmental Finance Center (EFC) for years 2014, 2015, 2017, and 2019 covering around 400 utilities. In these data I observe, utility name, county, approximate population served, number of connections, type of rate structure, date of last rate change, and monthly bill amounts at different consumption levels for both residential and non-residential customers. Later in this section I detail how these bill amounts are used to compute average marginal prices.

4.2 Revenue and Expenditure

I compile revenue and expenditure data from several sources. I include these data from a public records request for community water service (CWS) providers.[6] For non-CWS utilities, I use operating ratio[7] if available from EFC data[8] to approximate revenue and expenditure. Otherwise, I manually collect PDF files of city and county annual financial reports through Google searches as well as the Arizona Financial Transparency Portal.[9]

[6] A CWS is a public water system that serves at least 15 connections used by year-round residents or regularly serves 25 or more year-round residents. A non-CWS is a public water provider that has at least 15 service connections or regularly serves an average of at least 25 individuals daily, but does not serve year-round residential populations.

[7] Operating Ratio is operating revenue divided by expenditure including depreciation and amortization.

[8] For years 2014, 2015, and 2017 I observe the utility's operating ratio, the ratio of revenue to operating expenditure in the EFC data. For later years I compile revenue and expenditure data by hand from annual reports provided by the Arizona Corporation Commission.

[9] Arizona Financial Transparency Portal: https://www.azcc.gov/utilities/industry-types/water/annual-reports

4.3 Arizona Supply and Withdrawal Quantities

I submit public records requests to the Arizona Department of Water Resources (ADWR) to obtain annual utility-level supply and withdrawal quantities in acre feet (AF). These data provide annual utility-level quantity of water supplied to single-family, multi-family, non-residential, and other customers. I also observe the quantity of water withdrawn by source type. Source type is broken out to groundwater (GW), surface water (SW), Colorado River, water from the Central Arizona Project (CAP), and other.[10] I match 194 utilities with rates and supply data for all four years.

4.4 Central Arizona Project

I collect annual data on quantity of water purchased from CAP by entity and contract type, CAP water rates, and quantity of water stored in underground storage facilities (USF) and groundwater storage facilities (GSF) by entity through filing public records request.

I observe the quantity of water (in AF) purchased by year, utility, and contract type. Entities holding CAP contracts are permitted to lease water to other entities. For example, the City of Phoenix which holds a Municipal & Industrial (M&I) user contract may lease some or all of its contract allocation to another entity. More commonly observed however are large municipalities entering into leases to purchase additional CAP water from other entities with CAP contracts. I observe the quantity of water purchased under an entity's own contract and the quantity purchased through any leases along with the leasing entity.

The contract user type determines the delivery priority. In shortage years, total CAP water will see reductions; CAP then passes these reductions along to its users in order of user priority. Tribal users and M&I users are roughly equal in priority and are higher in priority than the non-Indian agriculture (NIA) user group as well as the excess group. Individual tribal use contracts may have higher priority than some M&I use contracts, which illustrates why some cities choose to lease water from tribes to hedge against reductions in their own contract entitlement.

The contract user type also determines the rate paid for the water ordered. Water that falls under a contract for municipal and industrial customers pays a CAP base rate ($/AF) plus a capital charge ($/AF) that is used to pay the federal government back for the costs incurred in the construction of the canal and infrastructure used to transport water to Central Arizona.

[10] Other includes reclaimed water.

4.5 Variable Construction

From the rates data, I construct average marginal price (AMP) between each consumption threshold as in Wichman (2024). For example, $AMP_{4kgal} = [Bill_{4kgal} - Bill_{0kgal}]/4$, $AMP_{5kgal} = [Bill_{5kgal} - Bill_{4kgal}]$, $AMP_{10kgal} = [Bill_{10kgal} - Bill_{5kgal}]/5$, $AMP_{15kgal} = [Bill_{15kgal} - Bill_{10kgal}]/5$, $AMP_{25kgal} = [Bill_{25kgal} - Bill_{15kgal}]/10$, $AMP_{50kgal} = [Bill_{50kgal} - Bill_{25kgal}]/25$, $AMP_{100kgal} = [Bill_{100kgal} - Bill_{50kgal}]/50$. These variables allow me to capture approximate marginal price changes across different levels of consumption. I include larger AMP thresholds than Wichman (2024) because several utilities in my data set have an average monthly demand per connection greater than 25kgal and I want to capture potential marginal price increases for large-volume non-residential customers.

4.6 Summary Statistics

Table 1 displays summary statistics for the core data needed for the empirical exercise detailed in the next section. One advantage of the setting for this study over previous is that I observe utility-level annual quantity supplied. As shown in the table, about 80% of utilities' water supply comes from groundwater, another 10% from the Colorado River, 2% from other surface water sources, and the remaining 4% from reclaimed water on average. There is wide variation across utilities in average monthly supply per connection. However, the mean and median fall in the range of average family monthly water consumption.[11] Utilities in my sample earn approximately 9 percent above operating costs on average.

The sample is primarily made up of small, groundwater-dependent utilities. The median utility serves 874 connections drawing 100 percent of its supply from groundwater, and both the 50th and 90th percentile of the groundwater share equal one. The mean connection count of 8,432 is an order of magnitude larger than the median, reflecting the presence of a small number of large metropolitan systems, including Phoenix, Tucson, and Mesa, that account for the bulk of Arizona's total water consumption despite representing a fraction of the utility count. The Colorado River share distribution is similarly bimodal: the median utility holds no CAP contract at all, while the 90th percentile reaches 47 percent. I use the full sample of 194 utilities for demand elasticity estimation and marginal cost estimation, exploiting the price and quantity variation that spans this heterogeneous population. The structural dynamic model and welfare simulations, however, are calibrated to and applied exclusively to the 21 CAP-dependent utilities, where the stochastic supply problem

[11] The Environmental Protection Agency (EPA) estimates the average family uses more than 300 gallons of water per day or about 9,000 gallons per month (EPA, 2024).

is empirically operative and the scarcity rent is nonzero. Results from the full-sample estimation inform the model's demand parameters; the model itself speaks to a narrower but policy-relevant set of utilities that face the intertemporal trade-off at the center of the Ramsey pricing problem.

Table 1: Summary Statistics

	Mean	SD	10th %ile	Median	90th %ile	N
Service Population	26,953	124,443	215	2,088	38,016	822
# of Connections	8,432	34,512	100	874	16,799	822
Total Annual Supply (AF)	5,469	26,239	19	296	6,820	842
Supply per Connection (kgal/month)	12.32	15.64	2.69	8.84	22.05	822
Operating Ratio (Rev./Exp.)	1.09	0.25	0.77	1.08	1.35	321
AMP_{4kgal} ($/kgal)	2.50	1.71	0.80	2.25	4.00	841
AMP_{5kgal} ($/kgal)	3.27	2.04	1.25	3.00	5.48	841
AMP_{10kgal} ($/kgal)	3.56	2.26	1.42	3.11	5.87	841
AMP_{15kgal} ($/kgal)	4.38	3.33	1.65	3.61	7.72	841
AMP_{25kgal} ($/kgal)	4.46	3.49	1.65	3.72	7.74	842
AMP_{50kgal} ($/kgal)	4.71	3.85	1.75	3.85	8.00	842
$\text{AMP}_{100kgal}$ ($/kgal)	4.85	4.05	1.80	3.94	8.95	842
Groundwater	0.84	0.33	0.11	1.00	1.00	839
Surface Water	0.02	0.11	0.00	0.00	0.00	839
Colorado Riv. Share	0.10	0.26	0.00	0.00	0.47	839

Notes: Utility-year observations from the Arizona water utility panel, 2014–2019. N varies across variables due to missing financial and supply records. Supply shares (groundwater, surface water, Colorado River) sum to approximately one when reclaimed water is included. The distribution of groundwater dependence is highly bimodal: 57 percent of utility-years report a groundwater share of one, and the 90th percentile also equals one. CAP-dependent utility-years are a distinct minority concentrated in the Phoenix and Tucson metropolitan service areas.

5 Demand Estimation

I estimate residential and non-residential demand separately by two-stage least squares, instrumenting for the endogenous marginal price with the average marginal price charged by neighboring utilities in the same county, lagged one period. The identification challenge is standard: utilities with higher demand set higher prices, so OLS estimates of the price coefficient are attenuated toward zero. The instrument follows the cross-market price strategy introduced by Hausman et al. (1994) and applied prominently by Nevo (2001). The identifying assumption is that utilities within the same county share common cost conditions—similar aquifer depth, comparable construction and regulatory costs, and exposure to the same county-level input price environment—but set prices in response to their own local demand. A change in a neighboring utility's price therefore signals a common cost shift rather than a correlated demand shock, satisfying the exclusion restriction. The leave-one-out construction, which excludes utility i from the county average, prevents any mechanical correlation between the instrument and the endogenous price. Lagging by one period eliminates contemporaneous simultaneity: a utility's own current-period demand shock cannot have caused neighboring utilities' rate decisions in the prior year, as water rate changes require formal regulatory approval and are set in advance (Hanemann, 1998). I apply the same strategy to the fixed fee, constructing a second instrument as the lagged leave-one-out county average of fixed charges. MacKay and Miller (2025) formalize the conditions under which cross-market price instruments of this type identify the price parameter, showing that identification requires the unobserved demand shock in the focal market to be mean-independent of prices in neighboring markets conditional on observables—a condition satisfied here by the combination of county-by-year fixed effects and the one-period lag. The general form of the instrument for sector s in utility i, county c, and year t is:

$$\bar{P}_{s,c,t-1} = \frac{\sum_{1}^{N-1} P_{s,j,c,t-1}}{N-1} \quad \forall \quad j \neq i$$

where N is the number of utilities in county c at year $t-1$.

The general form of the log-log (in quantity and price) demand estimation regression is:

$$q_{sict} = \beta_1 \widehat{P}_{sict} + X'_{ict}\gamma_1 + \eta_{ct} + \epsilon_{ict} \tag{20}$$

where q_{sict} is the equilibrium water quantity (in AF) sold in sector s of utility i in county c in year t, $\hat{P}_{ict}$ is the fitted value of price from the first stage regression for sector s of utility i in county c in year t, X_{ict} are controls, η_{ct} are county-by-year fixed effects, and ϵ_{ict} is the error term.

The first stage regression to obtain the fitted values of water prices is:

$$P_{sict} = \beta_2 \bar{P}_{s,c,t-1} + X'_{ict}\gamma_2 + \psi_{ct} + v_{sict} \tag{21}$$

where both P_{sict} and $\bar{P}_{s,c,t-1}$ are in logs. I instrument for water price with $\bar{P}_{s,c,t-1}$ which is the average sectoral water price within that utility's county, lagged one period. ψ_{ct} are county-by-year fixed effects and v_{sict} is the error term.

5.1 Residential Water Demand

Table 2 presents estimates of the residential demand equation. I treat both volumetric price (AMP_{ict} and AP_{ict}) and the fixed monthly fee as endogenous, instrumenting for each with the corresponding lagged county-mean price among all other utilities in the same county. Both the average marginal price (AMP_{ict}) and average price (AP_{ict}) at 10 kgal of consumption yield similar elasticity estimates of -0.59 and -0.54 respectively. First-stage F-statistics for the marginal price instrument and for the fixed-fee instrument are well above conventional thresholds for instrument strength. The fixed fee elasticity estimates are statistically insignificant and I cannot conclude that the monthly fixed fee alters consumption levels. The income elasticity is 0.93, consistent with water being a normal good with moderate income sensitivity. I use $\hat{\varepsilon}_1 = -0.59$ throughout the model calibration for residential water demand elasticity.

The direction of OLS bias is as expected. The OLS estimate of the price coefficient is -0.51 in Column (1), less elastic in absolute value than the IV estimate, reflecting the standard upward bias from endogenous rate-setting: utilities facing high demand set higher prices, attenuating the measured price response. The IV estimate corrects for this simultaneity by isolating variation in marginal prices driven by changes in neighboring utilities' rates rather than by demand conditions within the utility itself.

5.2 Non-Residential Water Demand

I estimate non-residential demand following the same IV strategy, treating the commercial volumetric price and fixed fee as endogenous and instrumenting with their lagged county-mean counterparts. The dependent variable is the log of non-residential water delivered per commercial establishment, where establishment counts are from the Census ZIP Business Patterns survey allocated to utility service areas by area-proportional intersection. This quantity-per-establishment measure standardizes for differences in the commercial density of utility service areas and isolates the intensive margin response of individual establishments to price.

Table 3 presents results for three alternative price measures. Column (1) uses the average marginal price in the 25–50 kgal per month consumption tier, the range most representative of moderate-scale non-residential users; Column (2) uses the 10–25 kgal tier; Column (3) uses the volumetric average price at 50 kgal. All three specifications yield price elasticities in a tight range: -0.82, -0.78, and -0.83, respectively, with Column (1) and Column (3) significant at the 10 per-

Table 2: Residential Water Demand

	(1) OLS	(2) IV	(3) IV
AMP_{ict}	-0.51***		
	(0.12)		
$\widehat{AMP}_{ict}$		-0.59**	
		(0.26)	
$\widehat{AP}_{ict}$			-0.54**
			(0.26)
Fixed Fee$_{ict}$	0.10		
	(0.10)		
$\widehat{\text{Fixed Fee}}_{ict}$		-0.03	-0.11
		(0.19)	(0.17)
ln(Median Income)	0.93***	0.93***	0.94***
	(0.16)	(0.15)	(0.15)
Observations	526	526	526
County$\times$Year FE	✓	✓	✓
First-stage F: Price	—	93.7	88.6
First-stage F: Fixed Fee	—	139.8	137.4

Notes: The dependent variable is the natural logarithm of residential water delivered per capita. Column (1) is OLS. Columns (2) and (3) instrument for both the marginal price and fixed fee using lagged leave-one-out county averages of neighboring utilities' prices. *AMP* is the average marginal price at 10 kgal/month; *AP* is the average volumetric price. Standard errors clustered by utility in parentheses. Significance: ***=0.01, **=0.05, *=0.10.

cent level and Column (2) significant at the 5 percent level. First-stage F-statistics range from 14.2 to 16.6 for the price instrument and 19.9 to 20.5 for the fixed-fee instrument, indicating adequate instrument strength. I use $\hat{\varepsilon}_2 = -0.82$ from the preferred Column (1) specification in the model calibration for non-residential water demand elasticity.

Non-residential demand is more price-elastic than residential demand at -0.82 versus -0.59. The most plausible explanation is that non-residential establishments treat water as an input cost subject to profit maximization rather than a consumption good, which makes them systematically more attentive to marginal prices. A business that monitors operating costs through accounting has stronger incentives to reduce water-intensive processes, adjust scheduling, or adopt water-saving equipment when the price of a variable input rises. Residential users, by contrast, tend to be less price-responsive at the margin both because water expenditure is a small share of household income and because the perceived price signal is often muted by the complexity of block-rate billing structures (Ito, 2014; Wichman, 2014). The fixed-fee elasticity of 0.66 in Column (1) is imprecisely estimated, reflecting the limited variation in non-residential fixed charges and consistent with statistically insignificant estimates in the residential demand specification. The income coefficient is -2.0 across all specifications, indicating that utilities serving higher-income counties have substantially lower non-residential water use per establishment, consistent with a shift toward less water-intensive non-residential activity in wealthier communities.

6 Marginal Cost Estimation

The optimal pricing formula in equation (18) requires utility-year estimates of marginal cost c_i. I recover these from a log-linear cost function estimated on the panel of utility-year operating expenditures, following the approach in Wichman (2024). Estimating this elasticity directly from cost and quantity data therefore yields a utility-specific marginal cost without requiring observation of input prices.

6.1 Specification

I estimate separate cost regressions for AMA and non-AMA utilities: AMA utilities operate under the 100-year assured water supply requirement and tend to be larger, while non-AMA utilities are usually smaller and rely predominantly on groundwater extraction. Pooling the two groups

Table 3: Non-Residential Water Demand (Per Establishment)

	(1) OLS	(2) IV	(3) IV	(4) IV
AMP_{ict}^{com}	-0.72**			
	(0.33)			
$\widehat{AMP}_{ict}^{com}$ (25–50 tier)		-0.82*		
		(0.44)		
$\widehat{AMP}_{ict}^{com}$ (10–25 tier)			-0.78**	
			(0.36)	
$\widehat{AP}_{ict}^{com}$ (avg, 50 kgal)				-0.83**
				(0.41)
Fixed Fee_{ict}^{com}	0.32			
	(0.34)			
$\widehat{\text{Fixed Fee}}_{ict}^{com}$		0.66*	0.43	0.58
		(0.38)	(0.39)	(0.38)
ln(Payroll/Estab)	-0.29	-0.24	-0.27	-0.27
	(0.28)	(0.29)	(0.30)	(0.29)
ln(Median HH Income)	-2.05***	-2.0***	-2.1***	-2.1***
	(0.58)	(0.57)	(0.58)	(0.58)
Observations	392	392	392	392
County$\times$Year FE	✓	✓	✓	✓
First-stage F: Price	—	16.6	14.2	15.9
First-stage F: Fixed Fee	—	20.5	19.9	20.5

Notes: The dependent variable is the natural logarithm of non-residential water delivered per commercial establishment (kgal/yr). Establishment counts are from ZIP Business Patterns (ZBP), allocated to utility service areas via area-proportional ZCTA intersection. Column (1) is OLS using the average marginal price at the 50 kgal threshold (AMP_{50}). Columns (2)–(4) instrument for both the volumetric price and fixed fee using lagged leave-one-out county averages. Average payroll per establishment (ZBP, $1,000s) controls for establishment size. Standard errors clustered by utility. Significance: ***=0.01, **=0.05, *=0.10.

would require strong homogeneity assumptions across very different cost structures. Within the AMA sample, I interact the log-quantity term with a CAP-user indicator to allow the cost elasticity to differ for utilities with active CAP contracts, which face the additional variable cost of M&I contract water purchases.

The estimating equation is:

$$\ln(E_{it}) = \beta_1 \ln(Q_{it}) + \beta_2 \left[\ln(Q_{it}) \times \mathbf{1}(\text{CAP}_i)\right] + \eta_{ct} + \varepsilon_{it}, \tag{22}$$

where E_{it} is annual operating expenditure for utility i in year t (dollars), Q_{it} is total annual supply (kgal), $\mathbf{1}(\text{CAP}_i)$ is an indicator equal to one if the utility holds a CAP contract, and η_{ct} are county-by-year fixed effects that absorb common variation in input costs, drought severity, and regulatory conditions. Standard errors are clustered by utility to account for serial dependence in costs within utilities over time. The non-AMA regression omits the CAP interaction.

From equation (22), the implied marginal cost is:

$$\widehat{MC}_{it} = \hat{\beta}_{it} \cdot \frac{E_{it}}{Q_{it}} = \hat{\beta}_{it} \cdot AC_{it}, \tag{23}$$

where $\hat{\beta}_{it} = \hat{\beta}_1 + \hat{\beta}_2 \cdot \mathbf{1}(\text{CAP}_i)$ is the estimated cost elasticity for utility i and $AC_{it} = E_{it}/Q_{it}$ is the observed average cost. Marginal cost is therefore the product of the cost elasticity and average cost. The fixed cost component that must be recovered through the Ramsey markup is:

$$\hat{\tau}_{it} = (1 - \hat{\beta}_{it}) \cdot E_{it}, \tag{24}$$

which is the dollar amount of expenditure not attributable to variable production costs and which enters the budget constraint in equation (3) as the period fixed cost τ.

6.2 MC Estimates

Table 4 presents the cost function estimates. In the AMA sample (Column 2), the cost elasticity with respect to output is $\hat{\beta}_1 = 0.902$, implying that a 1 percent increase in total supply is associated with a 0.9 percent increase in operating expenditure. The CAP interaction adds $\hat{\beta}_2 = 0.031$ ($SE = 0.013$), so the cost elasticity for AMA utilities that purchase CAP water is 0.933, reflecting the higher variable costs associated with CAP water purchases relative to groundwater extraction. Non-AMA utilities (Column 3) exhibit greater economies of scale, with a cost elasticity of $\hat{\beta}_1 = 0.724$, consistent with small groundwater-dependent utilities operating with high fixed infrastructure costs relative to their volume of supply. This makes sense as purchasing groundwater rights is a one-time upfront cost, with the remaining variable costs associated with pumping, treatment, and delivery.

The implied marginal cost estimates have a median of $3.57 per kgal for CAP utility-years and $5.15 per kgal for non-AMA utility-years. For AMA utilities, the small difference between marginal and average cost ($\hat{\beta}_1 = 0.902$ implies $MC \approx 0.90 \times AC$) means the fixed cost component is modest and the optimal Ramsey markup required for budget balance is small relative to the marginal cost. For non-AMA utilities, the larger gap between MC and AC ($\hat{\beta}_1 = 0.724$) means the Ramsey markup would account for roughly 28 percent of average cost.

Table 4: Cost Function Estimates

	Pooled (1)	AMA (2)	Non-AMA (3)
ln(Q)	0.745***	0.902***	0.724***
	(0.035)	(0.050)	(0.044)
ln(Q)×CAP user	0.057***	0.031**	
	(0.011)	(0.013)	
Observations	581	156	425
R^2	0.91	0.96	0.82
County-Year fixed effects	✓	✓	✓

Note: Dependent variable: ln(operating expenditure). County×Year fixed effects. SE clustered by utility. $\widehat{MC}_{it} = \hat{\beta}_1 \times (E_{it}/Q_{it})$; AMA CAP utilities use $(\hat{\beta}_1 + \hat{\beta}_2) \times (E_{it}/Q_{it})$. Significance: ***=0.01, **=0.05, *=0.10.

7 Results

7.1 Optimal Prices

Table 5 reports the distribution of model-implied optimal prices for the residential and non-residential sectors across the four rate structure and CAP status groups. Residential optimal prices are evaluated at 10 kgal per connection per month and non-residential at 25 kgal per connection per month, matching the consumption benchmarks used throughout the demand estimation. For CAP utilities, p_1^* and p_2^* are solutions to the stochastic dynamic program evaluated at each utility-year's observed water stock; for non-CAP utilities, the scarcity component is zero and the benchmark collapses to average cost. The median optimal residential price for uniform-rate CAP utilities is \$3.81 per kgal and \$3.94 for non-residential, compared to medians of \$4.56 and \$4.68 for their IBR counterparts. Non-CAP utilities face substantially higher benchmarks, with medians of \$5.08 and \$5.67 per kgal for uniform and IBR utilities respectively, reflecting the higher average costs that prevail outside the CAP service area where groundwater extraction is the marginal supply source. These figures are economically plausible: median observed prices across the sample run \$3.06 to \$3.47 per kgal, placing the optimal benchmark 25 to 65 percent above what utilities currently charge.

Table 5: Model-Implied Optimal Prices by Sector and Rate Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Residential optimal, p_1^*	3.74	0.94	2.52	3.81	4.92	15
Non-residential optimal, p_2^*	3.85	0.97	2.47	3.94	5.02	15
Panel B: *Uniform rates, non-CAP utilities*						
Residential optimal, p_1^*	6.71	5.37	2.00	5.08	14.11	134
Non-residential optimal, p_2^*	6.71	5.37	2.00	5.08	14.11	134
Panel C: *IBR rates, CAP utilities*						
Residential optimal, p_1^*	5.09	2.08	3.48	4.56	9.12	31
Non-residential optimal, p_2^*	5.12	1.97	3.39	4.68	8.86	31
Panel D: *IBR rates, non-CAP utilities*						
Residential optimal, p_1^*	7.27	5.49	2.54	5.67	12.98	174
Non-residential optimal, p_2^*	7.27	5.49	2.54	5.67	12.98	174

Notes: Model-implied optimal prices in \$/kgal. For CAP utilities (Panels A and C), p_1^* and p_2^* are the residential and non-residential solutions to the stochastic dynamic program evaluated at the observed water stock (w_{it}, b_{it}). For non-CAP utilities (Panels B and D), the scarcity component is zero and the optimal price equals the average cost benchmark: $p_1^* = p_2^* = AC_{it}$. Sample restricted to IBR and uniform-rate utilities with $AC_{it} \leq \$30$/kgal. Years: 2014, 2015, 2017, 2019.

The residential and non-residential optimal prices track closely within each panel, differing by less than 15 cents at the median. Both are governed by the same theoretical decomposition (marginal cost plus the Ramsey markup plus the scarcity rent λ/μ), and the scarcity rent is common across sectors at a given utility-year since it reflects the shadow value of the shared water stock. The small positive gap between p_2^* and p_1^* reflects the difference in Ramsey markups: with non-residential demand more elastic ($\varepsilon_2 = -0.82$ versus $\varepsilon_1 = -0.59$), the inverse-elasticity rule implies a smaller markup per unit, but this effect is partially offset by non-residential customers accounting for a larger share of total revenue at the margin. That p_1^* and p_2^* are close but not identical is itself a result of the two-sector structure: a single-sector model would assign the same optimal price to all users, abstracting from the differential conservation incentives that sector-specific elasticities imply.

7.2 Observed Prices Relative to the Optimal Benchmark

The large majority of Arizona utilities price water below the cost-recovery benchmark, and virtually all price below the scarcity-inclusive optimum I derive from the dynamic program. Among the 241 non-AMA utility-years in the trimmed sample, 91 percent charge prices below average cost, confirming the systematic cost-recovery failures documented by McRae (2015) and Wichman (2024). The median observed price is \$3.47 per kgal against a median average cost of \$6.19, a shortfall of \$2.88 per kgal. These utilities face no formal groundwater constraint in the model and no CAP exposure, so the benchmark is cost recovery alone; their true optimal price would be higher still once groundwater depletion externalities are incorporated.

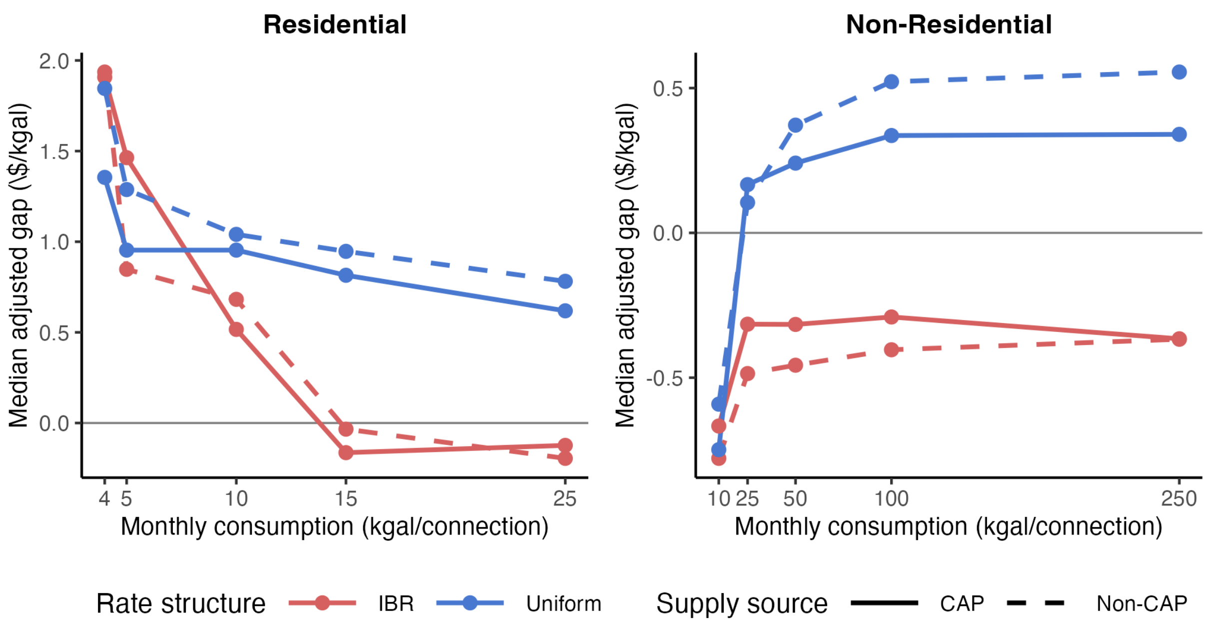
AMA utilities without CAP contracts price closer to average cost but still fall short. Among the 67 AMA non-CAP utility-years, 63 percent price below average cost, with a median gap of \$0.75 per kgal. The Arizona Department of Water Resources' 100-year assured water supply requirement disciplines investment decisions but does not directly bind annual rate-setting, which explains why regulation reduces but does not close the gap.

The 46 CAP utility-years, for which I compute the full scarcity-inclusive optimal from the dynamic program, reveal the additional cost of ignoring the resource constraint. The median observed price is \$3.06 per kgal against a median average cost of \$3.82 and a median model-implied optimum of \$4.26. Assuming that observed price is equal to marginal cost, the \$1.20 per kgal gap between observed and optimal can be decomposed into a fixed cost-recovery component of \$0.76 and a scarcity rent component of \$0.44, where the latter equals the model-implied λ/μ evaluated at the observed water stock. This decomposition is exact given the theoretical result in equation (18). Optimal price equals marginal cost plus the Ramsey markup plus the shadow value of water; the Ramsey markup is identified from the value function iteration (VFI) solution, and the residual is the scarcity rent. The typical CAP utility recovers its fixed costs only partially and embeds essentially none of the shadow value of CAP availability into observed prices.

7.3 Price Gaps by Consumption Tier and Rate Structure

Figure 3 plots the median adjusted price gap against consumption level for residential (left panel) and non-residential (right panel) sectors, separately by rate structure and CAP status. The adjusted gap subtracts the Ramsey markup $(AC - MC)$ from p^* before comparing to the observed average marginal price, yielding a volumetrically comparable benchmark of $MC +$ scarcity component. Full distributional detail appears in Tables 8 and 9 in the appendix.

Figure 3: Median Adjusted Price Gap by Consumption Level, Rate Structure, and CAP Status



Notes: Median adjusted gap $= p^* - (AC - MC) -$ Avg. MP in \$/kgal, where a positive value indicates underpricing relative to the scarcity-inclusive benchmark. Residential gaps (left) are evaluated at 4, 5, 10, 15, and 25 kgal per connection per month; non-residential gaps (right) at 10, 25, 50, 100, and 250 kgal per connection per month. For non-CAP utilities the scarcity component is zero and the benchmark reduces to MC. Sample restricted to IBR and uniform-rate utilities with $AC \leq \$30/\text{kgal}$.

For uniform-rate utilities, the residential gap is positive and roughly flat across all consumption levels, declining only modestly from +\$1.36 per kgal at 4 kgal per month to +\$0.62 at 25 kgal per month. This flatness is mechanical: a uniform rate produces the same average marginal price at every consumption level, so the observed price falls short of the adjusted optimum by a roughly constant amount regardless of usage. IBR utilities exhibit a sharply different pattern. The median residential gap for IBR CAP utilities opens at +\$1.91 per kgal at 4 kgal per month and compresses to −\$0.16 by 15 kgal, a swing of more than \$2 per kgal. Negative gaps at upper tiers indicate that IBR upper-block prices exceed the adjusted optimum, effectively overpricing high-use residential consumption to cross-subsidize the heavily discounted first block. This pattern reveals a deliberate equity trade-off embedded in IBR design: low-volume residential users pay below the scarcity-inclusive price, while the conservation burden is concentrated at higher tiers.

The non-residential panel tells a complementary story. IBR utilities are persistently above the adjusted optimum across all non-residential consumption levels, with gaps that remain positive even at 250 kgal per month. Rather than compressing toward zero as in the residential panel, the non-residential gap for IBR utilities is broadly flat and elevated, suggesting that IBR schedules used for residential billing do not translate into meaningful price differentiation for non-residential accounts. The implication is that the conservation signal IBR sends to high-volume residential customers is not extended to non-residential users, whose higher price elasticity ($\varepsilon_2 = -0.82$) would make them the more cost-effective target for demand reduction. Uniform utilities show a similar non-residential profile, confirming that the sector-specific conservation failure is not unique to IBR but is common across rate structure types.

7.4 Welfare Simulation: Status Quo versus Optimal Pricing

The tier-table results establish that IBR utilities price high-use consumers closer to the scarcity-inclusive optimum on average, but they do not answer the welfare question: how much does persistent underpricing cost, and how do the costs differ across rate structure types? I address this with a 5-year forward simulation that computes the discounted expected utility gain from transitioning to model-optimal pricing for each of the 21 CAP utilities in the sample.

The simulation proceeds as follows. Starting from 20 percent of observed 2019 total demand as the initial water stock and 20 percent of observed 2019 revenue as the initial financial reserve, I draw sequences of CAP supply shocks $\{\theta_t\}_{t=1}^{5}$ from a calibrated Beta distribution and propagate the state forward under each pricing scenario. Under the status quo scenario, prices are held fixed at observed 2019 levels and the utility purchases CAP water according to the VFI policy function evaluated at the status quo state. Under the optimal scenario, I evaluate the VFI policy functions at each realized state (w_t, b_t) to obtain the period-t optimal prices and CAP purchase decision. The simulation is repeated for 500 shock sequences. I compute results under two shock regimes: a mild regime representing recent normal conditions and a stressed regime calibrated to conditions more severe than Colorado River Tier 3 shortage declarations.[12] I evaluate the welfare change

[12] The mild regime draws $\theta \sim \text{Beta}(50, 1)$, implying mean CAP delivery of approximately 98 percent of contract. The stressed regime draws $\theta \sim \text{Beta}(4, 1)$, implying mean delivery of 80 percent of contract and approximately 6 percent

as $V^*(w_t^{\mathrm{OPT}}, b_t^{\mathrm{OPT}}) - V^*(w_t^{\mathrm{SQ}}, b_t^{\mathrm{SQ}})$ at the post-transition state in each period, then divide by the number of connections to obtain a per-connection figure in dollars.

The unit cost of purchased CAP water, p_x, is calibrated differently across the two regimes to reflect how shortage conditions affect delivery pricing. Under the mild regime, p_x follows the 2019 observed M&I delivery rate of \$0.485 per kgal grown forward at 2.5 percent per year to account for structural cost inflation, yielding a path-independent schedule $p_x(t) = 0.485 \times 1.025^t$ for simulation years $t = 1, \ldots, 5$. Under the stressed regime, p_x is tied to each period's shock realization: $p_x(\theta_t) = 0.90 + (1 - \theta_t)$, so each reduction in contract delivery raises the per-unit cost proportionally. This functional form is motivated by the post-2022 CAP rate data shown in Figure 6 in the appendix. As that figure illustrates, delivery rates exhibited no statistically significant relationship with delivery volume during the pre-shortage period from 2014 to 2021, but from 2022 onward under Drought Contingency Plan conditions, delivery reductions and rate increases were tied to the same shortage tier, generating a strong negative correlation between deliveries and price per unit that was absent before. At the mean stressed delivery level ($\theta = 0.80$), this implies $p_x = \$1.10$ per kgal, roughly double the mild-regime rate in year one. The stressed scenario therefore applies pressure through two simultaneous channels. The same shock θ that limits available purchase volume ($\bar{x}(\theta_t) = \bar{x} \cdot \theta_t$) also raises the per-unit cost, amplifying the budget constraint's bite and increasing the marginal value of demand reduction through higher prices.

Table 6: Discounted Expected Utility Gain from Optimal Pricing

	Mild Scenario	Stressed Scenario
IBR ($n = 15$)	\$54.1 [\$-1.4, \$170.3]	\$2.9 [\$-0.3, \$75.3]
Uniform ($n = 6$)	\$37.6 [\$6.7, \$98.1]	\$11.6 [\$0.0, \$39.9]

Notes: Median discounted expected utility gain per connection (\$/conn), pooled across all Monte Carlo paths and simulation years. Interquartile range in brackets. CAP utilities only ($n = 21$). Mild regime: mean CAP delivery $\approx$ 98% of contract, low variance. Stressed regime: mean delivery = 80% of contract, higher variance consistent with Tier 3 shortage conditions.

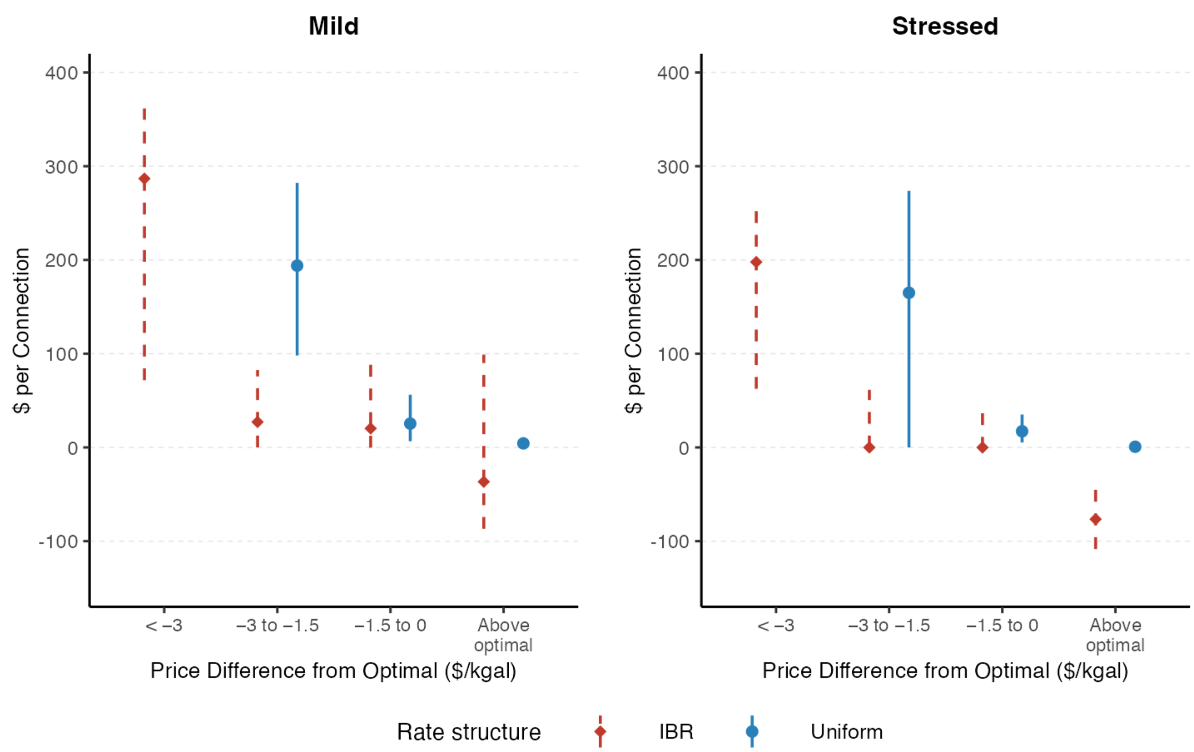
Table 6 reports median welfare gains per connection across all 21 CAP utilities. In mild supply conditions, the IBR full-sample median is \$54 per connection, about 44% greater than the uniform median. This comparison, however, is shaped by a small number of severely underpriced IBR utili-

probability of delivery below half of contract.

ties whose gains are mechanically large; Figure 4 disaggregates the distributions by the magnitude of each utility's observed price deviation, clarifying where the full-sample contrast originates.

Figure 4 organizes the results by how far each utility's observed residential price deviates from the model optimum. The x-axis divides the 21 utilities into four bins based on the signed gap $p_1^{obs} - p_1^*$: below $-\$3$, $-\$3$ to $-\$1.50$, $-\$1.50$ to $\$0$, and above the optimum. The y-axis reports the median discounted welfare gain per connection, with interquartile range bars; red diamonds represent IBR utilities and blue circles represent uniform-rate utilities. The left and right panels display the mild and stressed regimes respectively.

Figure 4: Discounted Expected Welfare Gain from Optimal Pricing, by Price Deviation and Rate Structure



Notes: Each point plots the median discounted welfare gain per connection ($V^*(w_t^{OPT}, b_t^{OPT}) - V^*(w_t^{SQ}, b_t^{SQ})$, in \$/connection) across 500 Monte Carlo paths and 5 simulation years, for utilities grouped by the signed gap $p_1^{obs} - p_1^*$ (in \$/kgal). Interquartile range bars shown. Red diamonds: IBR utilities ($n = 15$). Blue circles: uniform-rate utilities ($n = 6$). Left panel: mild regime, $\theta \sim \text{Beta}(50, 1)$, mean delivery $\approx$ 98% of contract. Right panel: stressed regime, $\theta \sim \text{Beta}(4, 1)$, mean delivery $=$ 80% of contract. No uniform-rate utilities fall in the $< -\$3$ bin.

Under the mild regime, the welfare gains are broadly comparable across rate structure types for utilities whose observed prices fall within \$1.50 of the optimum. In the $-\$1.50$ to \$0 bin, IBR utilities achieve a median gain of \$20 per connection and uniform-rate utilities a median of \$25. In the $-\$3$ to $-\$1.50$ bin, by contrast, the two uniform-rate utilities (Paradise Valley and Oro Valley) achieve a median of \$194 per connection against \$27 for the three IBR utilities in that bin (Eloy, Surprise, and Sun City). Four IBR utilities fall in the above-optimal bin, meaning the model predicts their observed prices exceed the efficient level;[13] their median gain is $-\$37$, reflecting the cost of moderate overpricing in mild conditions.

The stressed regime reveals a sharper pattern. In the $-\$1.50$ to \$0 bin, IBR utilities' median gain falls to \$0 while uniform-rate utilities retain a median of \$17 per connection. In the $-\$3$ to $-\$1.50$ bin, the IBR median collapses from \$27 in the mild case to essentially \$0, while the uniform-rate median declines only modestly from \$194 to \$165. Across all moderate deviation bins, uniform-rate utilities preserve a meaningful positive welfare gain under stressed supply conditions while IBR utilities do not.

Three IBR utilities fall in the leftmost bin, with observed prices between \$4.80 and \$6.13 per kgal below the model optimum.[14] The resulting welfare gains reach \$200 to \$290 per connection under mild conditions, mechanically large and driven by the severity of structural underpricing rather than rate structure type. These three utilities account for the elevated IBR median in Table 6 and motivate the trimmed comparison below.

Table 7: Discounted Expected Utility Gain from Optimal Pricing (Excluding Severely Underpriced Utilities)

	Mild Scenario	Stressed Scenario
IBR ($n = 12$)	\$11.0	\$0.0
	[\$-11.7, \$86.6]	[\$-9.7, \$44.7]
Uniform ($n = 6$)	\$37.6	\$11.6
	[\$6.7, \$98.1]	[\$0.0, \$39.9]

Notes: Median discounted expected utility gain per connection (\$/conn), pooled across all Monte Carlo paths and simulation years. Interquartile range in brackets. Three IBR utilities with observed prices more than \$3/kgal below optimal are excluded; their gains are driven by severe structural underpricing rather than rate structure per se. Uniform utilities unchanged ($n = 6$). Mild regime: mean CAP delivery $\approx$ 98% of contract, low variance. Stressed regime: mean delivery = 80% of contract, higher variance consistent with Tier 3 shortage conditions.

Restricting attention to utilities with price deviations greater than $-\$3$ per kgal, the sample that enables a cleaner comparison at more typical underpricing levels, reverses the ordering. The

[13] Tucson, Agua Fria, Mesa, and Vail.

[14] Cave Creek, Florence, and Goodyear. Model-implied optimal prices range from \$7.04 (Florence) to \$9.38 (Cave Creek) against observed prices of \$2.19 to \$4.48.

trimmed sample comprises 12 IBR and 6 uniform-rate utilities. Under the mild regime, the IBR median falls to \$11 per connection against a uniform median of \$37.6. The divergence is more pronounced under the stressed regime: the IBR median collapses to \$0 while the uniform median retains \$11.6.

The pattern that welfare gains are smaller under the stressed distribution than the mild distribution applies to both rate structure types and reflects the intertemporal mechanism through which optimal pricing generates value. Under mild supply conditions, a utility pricing at the model optimum can accumulate water stocks and financial reserves during favorable years, building the resource cushion that provides insurance against future shortfall. A utility on the status quo path, holding prices below the optimum, accumulates less stock and enters future periods with a weaker reserve position. The welfare gain from transitioning to optimal pricing captures this divergence through the dynamic program's value function. Although the simulation runs for five years, V^* is the solution to the infinite-horizon Bellman equation, so evaluating $V^*(w_t^{\text{OPT}}, b_t^{\text{OPT}}) - V^*(w_t^{\text{SQ}}, b_t^{\text{SQ}})$ at each period's realized state incorporates the full continuation value of accumulated stocks and reserves—including at the terminal period, where the state (w_5, b_5) is valued at $V^*(w_5, b_5)$ rather than discarded, with V^* capturing expected surplus beyond the simulation window. Under the stressed distribution, CAP deliveries are persistently compressed and the opportunity for early-period stockpiling is limited, so the insurance mechanism operates under tighter constraints and the welfare gap between the two paths narrows.

The near-zero IBR welfare gain under the stressed regime also reflects how the simulation represents IBR pricing, and is itself a substantive finding. The welfare calculation uses the average marginal price at 10 kgal per connection per month as the single observed price for each IBR utility. When that rate already approximates the model-optimal level, a pattern the tier-table analysis in Section 7.3 confirms for moderate consumption levels, the aggregate gain from transitioning to the uniform-equivalent optimum is correspondingly small. IBR pricing, by concentrating higher prices at upper tiers, brings the marginal rate for moderate consumers closer to the scarcity-inclusive optimum than a flat uniform rate set far below the optimal level. What the simulation does not resolve is how the gains and losses from a transition to optimal uniform pricing would be distributed across the full tier schedule. Low-use residential customers, who pay a subsidized first-block price below the scarcity-inclusive optimum, would incur a consumer surplus loss under the transition; high-use customers, whose upper-block prices often exceed the optimal rate, would see their consumer surplus rise. Whether the net distributional effect favors or disfavors the transition depends on the number of customers at each tier, which is left for future research.

Two considerations bear on the scope of the results. First, the observed price for IBR utilities is constructed as the average marginal price at a fixed consumption level of 10 kgal per month, a single-point proxy for the full tier schedule; utilities with steep upper tiers will appear more underpriced than they truly are in this framework, because the AMP at 10 kgal understates the price paid by heavy users. Second, the model-optimal price is a uniform-equivalent rather than an optimal IBR tier schedule; a model that solved directly for the optimal block structure would quantify the within-schedule distributional effects described above. Neither consideration alters the core finding: the figures in Table 7 measure the welfare gain from moving each utility's observed price to the scarcity-inclusive optimum, and uniform-rate utilities capture larger gains than IBR utilities at typical underpricing levels. The equity question of how those gains and losses are distributed across the customer base remains an important open question and a natural extension of this work.

8 Conclusion

This paper asks which rate structures best embed the scarcity rent of water into prices, and by how much Arizona utilities fall short of the Ramsey-optimal benchmark. I address both questions with three complementary components. First, I assemble the most comprehensive utility-level water pricing panel for any U.S. state, linking billing schedules, supply quantities, financial records, and CAP delivery data for 194 Arizona utilities over 2014–2019. Second, I estimate residential and non-residential price elasticities of -0.59 and -0.82, using variation in neighboring utilities' prices as an instrument for average marginal price. Third, these estimates enter a two-sector stochastic dynamic program calibrated to each utility-year, yielding a scarcity-inclusive optimal price for each of the 21 CAP utilities in the sample. The results reveal systematic and substantial underpricing: 91 percent of non-AMA utility-years set prices below average cost, and the median CAP utility prices \$1.20 per kgal below the model optimum, with \$0.76 attributable to unrecovered fixed costs and \$0.44 to a scarcity rent that is essentially absent from observed rate schedules. Rate structure shapes where this shortfall is concentrated. IBR utilities price moderate consumers substantially closer to the scarcity-inclusive optimum than their uniform-rate counterparts, and this proximity translates into meaningfully smaller welfare losses under stressed supply conditions. Among utilities at typical underpricing levels, the IBR median welfare loss approaches zero under the stressed scenario while the uniform-rate median retains a gap of \$11.60 per connection, reflecting the larger and more persistent distance of a flat rate from the optimal.

The analysis proceeds at the utility level, and two limitations follow from this. The welfare figures measure the aggregate gain from transitioning from observed to optimal pricing at the average marginal rate. The results do not account for how those gains and losses would be distributed across consumers within a utility. Under a transition from an IBR schedule to optimal uniform pricing, low-use residential customers currently paying below the scarcity-inclusive first-block price would incur a consumer surplus loss, while high-use customers on elevated upper tiers would gain. The extent to this tradeoff and the precise conservation vs equity effects depend on the distribution of customers across consumption tiers, information not available in the data. The model-optimal price is also a uniform-equivalent rather than an optimally designed IBR schedule. The second-best block structure that jointly satisfies efficiency, cost recovery, and distributional objectives is a natural extension to this study and left for future work.

The findings carry a direct message for water regulators and utility managers. In most Arizona jurisdictions, rates are set through administrative proceedings that are infrequent and politically costly to revise. A utility that sets prices too low in one rate case may be unable to correct the error for several years. The choice of rate structure at the time of ratesetting therefore has lasting consequences for how well prices signal conservation, recover costs, and preserve the financial resilience needed to absorb supply shocks. IBR schedules provide a more durable approximation of the scarcity-inclusive optimum than uniform schedules: by concentrating higher prices at upper tiers, they deliver a meaningful conservation signal to high-use customers while being able to shift cost recovery burdens off of low-use customers. This advantage is most apparent under stressed supply conditions, precisely when the scarcity rent is highest and the cost of underpricing is largest. As Colorado River shortage declarations deepen and CAP delivery uncertainty grows through the remainder of the decade, the rate structure chosen today will determine how much of that cost falls on utilities, ratepayers, and the water stock itself.

Two extensions follow directly from these findings. The most immediate is an analysis of the distributional consequences of rate reform. Quantifying the consumer surplus effects for low-, medium-, and high-use customers within each utility requires customer-level consumption data and would make it possible to evaluate the equity-efficiency tradeoff that IBR's tier structure implicitly makes. A second extension involves deriving the second-best IBR schedule, which would sharpen the welfare comparison between IBR and uniform pricing as institutional forms and provide regulators with a principled basis for tier design. Together, these extensions would translate the aggregate efficiency results here into distributional guidance that regulators can utilize in rate cases.

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A Additional Tables

Table 8: Residential Price Gap from Optimal, Adjusted for Two-Part Tariff Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 4 kgal/mo	1.45	1.05	0.17	1.36	2.81	15
Avg. MP at 5 kgal/mo	1.19	0.96	0.17	0.95	2.56	15
Avg. MP at 10 kgal/mo	0.82	1.14	-0.52	0.95	2.36	15
Avg. MP at 15 kgal/mo	0.74	1.14	-0.52	0.82	2.36	15
Avg. MP at 25 kgal/mo	0.59	1.07	-1.03	0.62	1.88	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	2.74	3.55	-0.47	1.85	7.91	134
Avg. MP at 5 kgal/mo	2.22	3.34	-0.82	1.29	7.11	134
Avg. MP at 10 kgal/mo	2.02	3.33	-0.82	1.04	6.46	134
Avg. MP at 15 kgal/mo	1.92	3.34	-0.85	0.95	6.29	134
Avg. MP at 25 kgal/mo	1.84	3.33	-1.00	0.78	6.29	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 4 kgal/mo	2.34	1.74	0.47	1.91	5.52	31
Avg. MP at 5 kgal/mo	1.78	2.04	-0.28	1.46	5.52	31
Avg. MP at 10 kgal/mo	1.29	1.94	-0.44	0.52	4.42	31
Avg. MP at 15 kgal/mo	0.06	2.33	-2.03	-0.16	2.80	31
Avg. MP at 25 kgal/mo	0.39	1.75	-1.48	-0.12	3.14	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	2.57	3.18	0.13	1.94	5.46	174
Avg. MP at 5 kgal/mo	1.57	3.16	-0.92	0.85	4.48	174
Avg. MP at 10 kgal/mo	1.35	3.14	-1.14	0.68	4.11	174
Avg. MP at 15 kgal/mo	0.20	3.42	-2.68	-0.03	2.55	174
Avg. MP at 25 kgal/mo	0.11	3.41	-2.79	-0.20	2.55	174

Notes: Adjusted gap $= p_1^* - (AC_{it} - MC_{it}) -$ Avg. MP_{it}, in \$/kgal. Avg. MP_{it} is the average marginal price for utility i in year t at the consumption level shown. MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6); AC_{it} is average cost. The model-optimal price p_1^* embeds a Ramsey markup $(AC_{it} - MC_{it})$ to recover fixed costs through the volumetric rate, because the model uses volumetric-only pricing. Observed utilities recover fixed costs through a fixed service charge, so their volumetric price is not expected to cover the Ramsey component. Subtracting the Ramsey markup from p_1^* yields the fair volumetric benchmark MC_{it} + scarcity component. Positive values indicate the observed price falls below the adjusted optimum (underpricing); negative values indicate overpricing. For non-CAP utilities (Panels B and D), the scarcity component is zero and the benchmark reduces to MC_{it}. Sample restricted to IBR and uniform-rate utilities with $AC_{it} \leq \$30$/kgal. Years: 2014, 2015, 2017, 2019. See Table 12 for the unadjusted gap (appendix).

Table 9: Non-Residential Price Gap from Optimal, Adjusted for Two-Part Tariff Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 10 kgal/mo	-0.81	0.91	-2.08	-0.75	0.27	15
Avg. MP at 25 kgal/mo	0.09	0.75	-0.96	0.17	1.03	15
Avg. MP at 50 kgal/mo	0.36	0.81	-0.81	0.24	1.44	15
Avg. MP at 100 kgal/mo	0.49	0.86	-0.59	0.34	1.66	15
Avg. MP at 250 kgal/mo	0.52	0.86	-0.44	0.34	1.70	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	0.08	3.57	-2.51	-0.59	4.66	134
Avg. MP at 25 kgal/mo	1.14	3.32	-1.72	0.10	5.58	134
Avg. MP at 50 kgal/mo	1.43	3.34	-1.40	0.37	5.93	134
Avg. MP at 100 kgal/mo	1.52	3.38	-1.35	0.52	6.11	134
Avg. MP at 250 kgal/mo	1.50	3.40	-1.40	0.56	6.17	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 10 kgal/mo	-0.48	1.18	-1.84	-0.67	1.38	31
Avg. MP at 25 kgal/mo	0.06	1.35	-0.96	-0.32	2.12	31
Avg. MP at 50 kgal/mo	0.03	1.27	-1.21	-0.32	1.71	31
Avg. MP at 100 kgal/mo	-0.11	1.05	-1.36	-0.29	1.64	31
Avg. MP at 250 kgal/mo	-0.34	0.96	-1.43	-0.37	1.24	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	-0.41	3.12	-3.09	-0.78	1.90	174
Avg. MP at 25 kgal/mo	-0.10	3.19	-2.66	-0.49	2.18	174
Avg. MP at 50 kgal/mo	-0.06	3.32	-2.72	-0.46	2.35	174
Avg. MP at 100 kgal/mo	-0.06	3.34	-2.83	-0.40	2.43	174
Avg. MP at 250 kgal/mo	-0.16	3.37	-2.92	-0.37	2.30	174

Notes: Adjusted gap $= p_2^* - (AC_{it} - MC_{it}) -$ Avg. MP_{it}, in \$/kgal. Avg. MP_{it} is the average marginal price for utility i in year t at the consumption level shown. MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6); AC_{it} is average cost. The model-optimal price p_2^* embeds a Ramsey markup $(AC_{it} - MC_{it})$ to recover fixed costs through the volumetric rate, because the model uses volumetric-only pricing. Observed utilities recover fixed costs through a fixed service charge, so their volumetric price is not expected to cover the Ramsey component. Subtracting the Ramsey markup from p_2^* yields the fair volumetric benchmark $MC_{it} +$ scarcity component. Positive values indicate the observed price falls below the adjusted optimum (underpricing); negative values indicate overpricing. For non-CAP utilities (Panels B and D), the scarcity component is zero and the benchmark reduces to MC_{it}. Sample restricted to IBR and uniform-rate utilities with $AC_{it} \leq \$30$/kgal. Years: 2014, 2015, 2017, 2019. See Table 13 for the unadjusted gap (appendix).

Table 10: Residential Price Markup above Marginal Cost by Consumption Tier and Rate Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	*n*
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 4 kgal/mo	-0.39	0.30	-0.71	-0.35	-0.02	15
Avg. MP at 5 kgal/mo	-0.30	0.26	-0.70	-0.23	-0.00	15
Avg. MP at 10 kgal/mo	-0.18	0.35	-0.64	-0.17	0.19	15
Avg. MP at 15 kgal/mo	-0.16	0.36	-0.64	-0.16	0.19	15
Avg. MP at 25 kgal/mo	-0.11	0.32	-0.41	-0.13	0.35	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	-0.26	0.90	-0.80	-0.49	0.20	134
Avg. MP at 5 kgal/mo	-0.11	1.10	-0.72	-0.35	0.46	134
Avg. MP at 10 kgal/mo	-0.06	1.08	-0.70	-0.30	0.38	134
Avg. MP at 15 kgal/mo	-0.04	1.08	-0.70	-0.27	0.46	134
Avg. MP at 25 kgal/mo	-0.02	1.09	-0.71	-0.25	0.52	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 4 kgal/mo	-0.42	0.28	-0.72	-0.45	-0.13	31
Avg. MP at 5 kgal/mo	-0.27	0.35	-0.64	-0.36	0.21	31
Avg. MP at 10 kgal/mo	-0.15	0.31	-0.55	-0.07	0.21	31
Avg. MP at 15 kgal/mo	0.15	0.45	-0.40	0.14	0.58	31
Avg. MP at 25 kgal/mo	0.08	0.31	-0.40	0.13	0.45	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	-0.34	0.51	-0.70	-0.43	-0.03	174
Avg. MP at 5 kgal/mo	-0.10	0.69	-0.60	-0.19	0.30	174
Avg. MP at 10 kgal/mo	-0.05	0.69	-0.56	-0.15	0.37	174
Avg. MP at 15 kgal/mo	0.20	0.86	-0.46	0.01	0.88	174
Avg. MP at 25 kgal/mo	0.21	0.85	-0.45	0.05	0.88	174

Notes: Markup $= (\text{Avg. MP}_{it} - MC_{it})/MC_{it}$, where MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6). Negative values indicate pricing below marginal cost; positive values indicate a markup above variable cost. See notes to the corresponding price-gap table for sample and panel definitions.

Table 11: Non-Residential Price Markup above Marginal Cost by Consumption Tier and Rate Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 10 kgal/mo	0.35	0.32	0.09	0.27	0.83	15
Avg. MP at 25 kgal/mo	0.07	0.27	-0.16	0.02	0.54	15
Avg. MP at 50 kgal/mo	-0.01	0.28	-0.27	-0.06	0.49	15
Avg. MP at 100 kgal/mo	-0.04	0.30	-0.33	-0.09	0.42	15
Avg. MP at 250 kgal/mo	-0.05	0.30	-0.35	-0.09	0.38	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	0.60	1.87	-0.50	0.15	1.26	134
Avg. MP at 25 kgal/mo	0.23	1.38	-0.59	-0.04	0.79	134
Avg. MP at 50 kgal/mo	0.13	1.24	-0.65	-0.09	0.71	134
Avg. MP at 100 kgal/mo	0.10	1.17	-0.69	-0.14	0.70	134
Avg. MP at 250 kgal/mo	0.11	1.18	-0.69	-0.14	0.68	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 10 kgal/mo	0.28	0.37	-0.22	0.28	0.75	31
Avg. MP at 25 kgal/mo	0.16	0.31	-0.32	0.20	0.58	31
Avg. MP at 50 kgal/mo	0.16	0.31	-0.30	0.20	0.47	31
Avg. MP at 100 kgal/mo	0.18	0.30	-0.19	0.20	0.52	31
Avg. MP at 250 kgal/mo	0.22	0.30	-0.05	0.25	0.54	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	0.40	1.00	-0.25	0.20	1.01	174
Avg. MP at 25 kgal/mo	0.28	0.90	-0.33	0.12	0.81	174
Avg. MP at 50 kgal/mo	0.27	0.91	-0.36	0.12	0.88	174
Avg. MP at 100 kgal/mo	0.26	0.92	-0.38	0.10	0.92	174
Avg. MP at 250 kgal/mo	0.28	0.94	-0.38	0.11	0.97	174

Notes: Markup = $(\text{Avg. MP}_{it} - MC_{it})/MC_{it}$, where MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6). Negative values indicate pricing below marginal cost; positive values indicate a markup above variable cost. See notes to the corresponding price-gap table for sample and panel definitions.

Table 12: Residential Price Gap from Optimal by Consumption Tier and Rate Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 4 kgal/mo	1.69	1.07	0.39	1.61	3.08	15
Avg. MP at 5 kgal/mo	1.43	0.98	0.39	1.10	2.81	15
Avg. MP at 10 kgal/mo	1.05	1.17	-0.28	1.10	2.61	15
Avg. MP at 15 kgal/mo	0.98	1.16	-0.28	1.07	2.61	15
Avg. MP at 25 kgal/mo	0.82	1.10	-0.79	0.77	2.18	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	4.48	5.03	0.35	2.89	11.80	134
Avg. MP at 5 kgal/mo	3.96	4.81	-0.19	2.50	10.99	134
Avg. MP at 10 kgal/mo	3.76	4.79	-0.25	2.34	10.31	134
Avg. MP at 15 kgal/mo	3.66	4.79	-0.48	2.30	9.82	134
Avg. MP at 25 kgal/mo	3.59	4.78	-0.58	2.30	9.82	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 4 kgal/mo	2.64	1.83	0.84	2.22	6.00	31
Avg. MP at 5 kgal/mo	2.09	2.13	-0.03	1.77	6.00	31
Avg. MP at 10 kgal/mo	1.60	2.03	-0.07	0.77	5.04	31
Avg. MP at 15 kgal/mo	0.37	2.39	-1.69	0.07	3.42	31
Avg. MP at 25 kgal/mo	0.69	1.83	-1.20	0.11	3.76	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 4 kgal/mo	4.42	4.65	0.77	3.21	9.23	174
Avg. MP at 5 kgal/mo	3.43	4.55	-0.03	2.08	8.12	174
Avg. MP at 10 kgal/mo	3.21	4.50	-0.23	1.83	7.73	174
Avg. MP at 15 kgal/mo	2.05	4.40	-1.56	1.12	6.48	174
Avg. MP at 25 kgal/mo	1.97	4.38	-1.56	1.01	6.26	174

Notes: Price gap = $p_1^* -$ Avg. MP_{it}, in \$/kgal. Avg. MP_{it} is the average marginal price for utility i in year t at the consumption level shown in each row. MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6). Positive values indicate the observed price falls below the scarcity-inclusive optimum (underpricing). For CAP utilities (Panels A and C), p_1^* is the solution to the stochastic dynamic program evaluated at the observed water stock. For non-CAP utilities (Panels B and D), $p_1^* = AC_{it}$, the average cost (cost-recovery lower bound). Sample restricted to IBR and uniform-rate utilities with $AC_{it} \leq \$30$/kgal. Years: 2014, 2015, 2017, 2019. See Table 8 for the two-part-tariff-adjusted gap (main results).

Table 13: Non-Residential Price Gap from Optimal by Consumption Tier and Rate Structure

	Mean	SD	10th %ile	50th %ile	90th %ile	n
Panel A: *Uniform rates, CAP utilities*						
Avg. MP at 10 kgal/mo	-0.57	0.93	-1.84	-0.54	0.53	15
Avg. MP at 25 kgal/mo	0.33	0.78	-0.74	0.35	1.35	15
Avg. MP at 50 kgal/mo	0.60	0.84	-0.59	0.40	1.77	15
Avg. MP at 100 kgal/mo	0.73	0.89	-0.35	0.56	1.97	15
Avg. MP at 250 kgal/mo	0.76	0.89	-0.21	0.59	2.00	15
Panel B: *Uniform rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	1.82	4.90	-2.03	0.45	8.29	134
Avg. MP at 25 kgal/mo	2.88	4.75	-1.07	1.53	9.03	134
Avg. MP at 50 kgal/mo	3.17	4.78	-0.90	1.83	9.40	134
Avg. MP at 100 kgal/mo	3.26	4.81	-0.88	2.02	9.61	134
Avg. MP at 250 kgal/mo	3.24	4.83	-0.87	2.01	9.72	134
Panel C: *IBR rates, CAP utilities*						
Avg. MP at 10 kgal/mo	-0.18	1.24	-1.45	-0.39	1.71	31
Avg. MP at 25 kgal/mo	0.36	1.43	-0.68	-0.10	2.61	31
Avg. MP at 50 kgal/mo	0.34	1.34	-0.98	-0.08	2.16	31
Avg. MP at 100 kgal/mo	0.19	1.11	-1.04	-0.03	1.89	31
Avg. MP at 250 kgal/mo	-0.03	0.97	-1.16	-0.01	1.50	31
Panel D: *IBR rates, non-CAP utilities*						
Avg. MP at 10 kgal/mo	1.44	4.38	-1.92	0.43	4.99	174
Avg. MP at 25 kgal/mo	1.76	4.31	-1.68	0.65	5.68	174
Avg. MP at 50 kgal/mo	1.79	4.36	-1.59	0.67	5.93	174
Avg. MP at 100 kgal/mo	1.79	4.34	-1.65	0.78	6.00	174
Avg. MP at 250 kgal/mo	1.70	4.32	-1.82	0.71	5.70	174

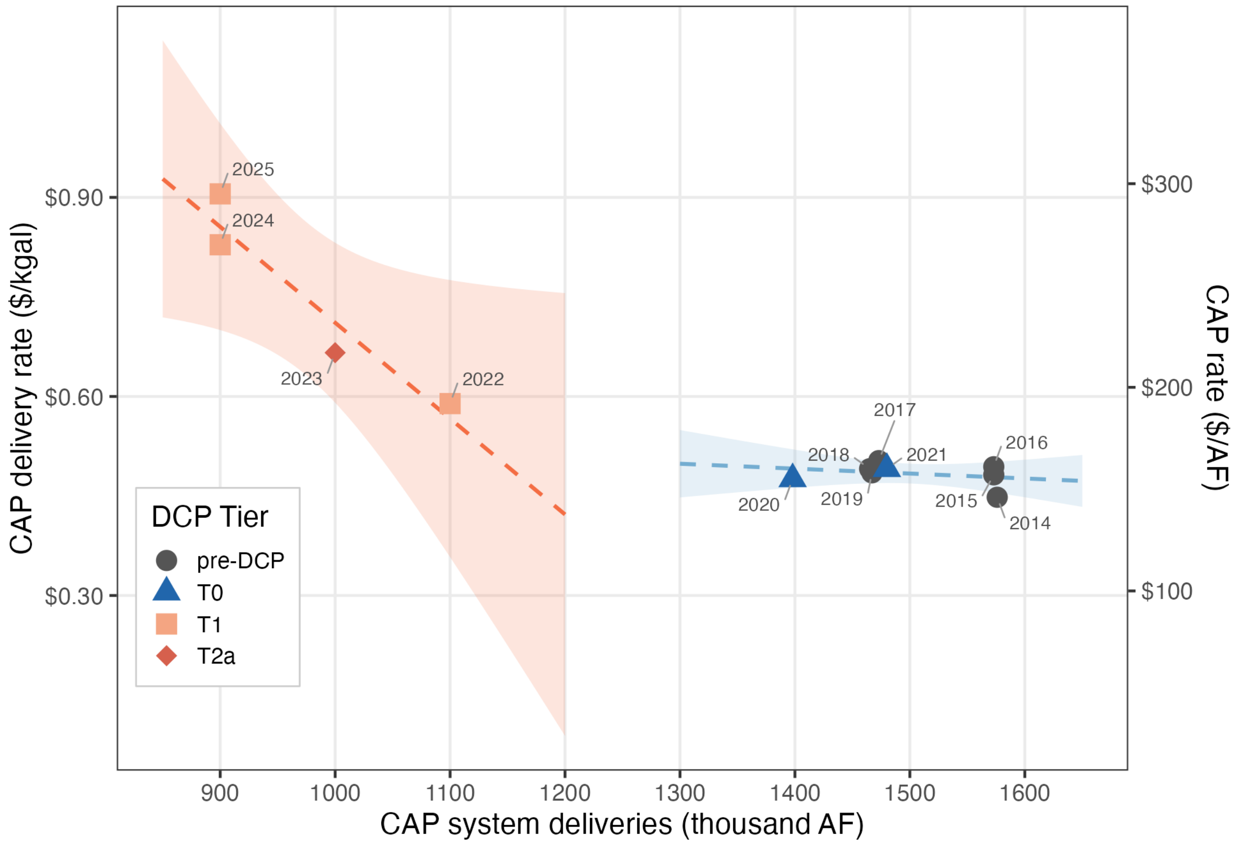
Notes: Price gap = $p_2^* - \text{Avg. MP}_{it}$, in \$/kgal. Avg. MP_{it} is the average marginal price for utility i in year t at the consumption level shown in each row. MC_{it} is the utility-year specific marginal cost estimate from the log-linear cost regression (Section 6). Positive values indicate the observed price falls below the scarcity-inclusive optimum (underpricing). For CAP utilities (Panels A and C), p_2^* is the solution to the stochastic dynamic program evaluated at the observed water stock. For non-CAP utilities (Panels B and D), $p_2^* = AC_{it}$, the average cost (cost-recovery lower bound). Sample restricted to IBR and uniform-rate utilities with $AC_{it} \leq \$30$/kgal. Years: 2014, 2015, 2017, 2019. See Table 9 for the two-part-tariff-adjusted gap (main results).

B Additional Figures

Figure 5: Central Arizona Project System Map

Notes: The Central Arizona Project aqueduct system diverts Colorado River water from Lake Havasu (western Arizona) eastward and southward through a 336-mile canal system to serve the Phoenix and Tucson metropolitan areas. Source: Central Arizona Project.

Figure 6: Central Arizona Project Delivery Volume and Price Relationship



Notes: The figure displays linear regressions of CAP delivered water price on total water delivered for two distinct periods. The early time period is represented by a blue dashed line and the more recent period is represented by an orange dashed line. In the early period of the Drought Contigency Planning (DCP) from 2014 to 2021, there is no statistically significant relationship between price of water and total amount delivered per year. For years 2022-2025, there is a strong negative correlation between CAP rate and amount delivered which is determined by DCP shortage tier.