Measuring the Welfare Losses from Urban Water Supply Disruptions

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Abstract

The paper evaluates welfare losses from urban water supply disruptions. The analysis incorporates important features of the water industry that may cause the initial allocation of water to be inefficient, namely that there are a large number of retail-level water utilities, and that most water utilities engage in a form of average cost pricing where volumetric rates are used to finance fixed expenses. We consider a sample of 53 urban water utilities in California collectively providing service to over 20 million customers. We calculate shortage losses for these utilities using existing water rates and utility-specific price elasticities derived from a demand estimation based on a panel data set of 37 California water utilities. Welfare losses for an annual 10% shortage ranging from an average of $1,458 per acre-foot of shortage to an average of $3,426 per acre-foot of shortage for a 30% supply disruption. The results indicate a household-level willingness-to-pay to avoid an annual shortage of approximately $60 to $600 depending on the shortage size and location. Beyond average losses, we also find evidence that there is substantial variation in shortage losses across utilities. For a 30% supply disruption, for example, the standard deviation across utilities of mean annual losses per acre-foot is $4,102.

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1 Introduction

In response to conditions of extreme drought and reduced water supplies, on May 15, 2015 California's lead regulatory agency for water imposed mandatory reductions on urban water use affecting nearly all of the state's urban water utilities (State Water Resources Control Board, 2015). This emergency intervention highlights the problem of urban water shortage facing water providers in California and beyond. The combination of variable water supplies, continued population growth, and increasing environmental constraints on urban water diversions underscores the importance of quantifying the welfare implications of water supply disruptions.

Urban water supply disruptions now occur in many areas of the United States. Atlanta, for example, has a rapidly growing urban population that relies primarily on diversions of surface water from the Chattahoochee River. As recently as 2007, drought and environmental concerns generated a water supply shortage in the region (Missimer et al., 2014). Similar scenarios of cities facing water supply disruptions are playing out notably in the states of Texas (Combs, 2012), Nevada (Barnett and Pierce, 2009), Colorado (Rajagopalan et al., 2009), Arizona (Marshall et al., 2010) and New Mexico (Martinez, Verhines, and Lopez, 2013), to name a few.

Beyond improving our understanding of the welfare costs of droughts and environmental restrictions, understanding the welfare loss from urban water shortages is also important when evaluating the costs and benefits of alternative water supplies. Desalination, for example, typically has a higher levelized cost than surface water supplies, but is also less prone to disruption. To compare the full range of costs and benefits of desalination versus more traditional supplies, it is important to measure the welfare consequences of periodic shortages, which are in a sense the inverse of a reliability premium.

Finally, the importance of measuring the welfare losses from urban water supply disruptions is increased with climate change and predicted reductions in water availability. As McDonald et al. (2011) point out, climate change will induce more frequent and prolonged periods of drought in the Southwestern United States. Hence the likelihood of water supply disruptions and adverse welfare impacts in this region may significantly increase.

In this article we evaluate welfare losses from an annual supply disruption for urban water users under existing infrastructure. We contribute three aspects to the literature on the economic cost of urban water shortages: (i) we incorporate an econometric model to account for regional variation in the price elasticity of residential demand; (ii) we measure welfare losses at a disaggregated level based on initial water prices that are not allocatively efficient; and (iii) we consider the role of fixed cost recovery when calculating welfare losses from shortage. These features of the analysis have important consequences for measuring the size and distribution of welfare losses from water shortages. In particular, we show that welfare losses from an urban water shortage can be significantly larger than suggested by measures of compensating or equivalent variation when water utilities respond by increasing rates or depleting financial reserves in response to a shortage. This circumstance is likely to occur when utilities recover fixed costs through volumetric rates, as is common in the industry. We also demonstrate that when the pre-shortage water allocation involves substantial variation in the marginal value of water across utilities (i.e., is allocatively inefficient), rationing can amplify these differences in marginal value, especially when there also exists variation in price elasticities of water demand across utilities.

Previous studies measuring welfare losses under a water supply disruption have employed contingent valuation methods (Griffin and Mjelde, 2000; Howe and Smith, 1994). In contrast, our analysis has the advantage of being based on actual valuations of water units by residential consumers as opposed to stated preferences over hypothetical scenarios. In this regard, our analysis is similar to Mansur and Olmstead (2012), which evaluates the inefficiency of command-and-control approaches, specifically a two day a week outdoor residential water restriction, to ration demand during times of supply disruption. In related work Grafton and Ward (2008) estimate an aggregate demand curve in Sydney, Australia to evaluate welfare losses resulting from mandatory restrictions on specific water uses instead of an efficient rationing mechanism such as raising prices. Brennan, Tapsuwan, and Ingram (2007) use a household production model from the labor economics literature to estimate the effects of sprinkler restrictions on consumer welfare as well as their efficacy. Our work complements this literature with analysis that considers welfare outcomes under different sets of assumptions (homogeneous price elasticities and initial prices versus heterogeneous price elasticities and initial prices across utilities; marginal cost and average cost pricing) and under two forms of water supply rationing (proportional rationing and efficient rationing). An important difference that separates our work from these other studies is that we consider changes in water utilities' supply costs; specifically, we account for how differences in fixed costs and customer bases affect volumetric prices.

We consider the economic impact of annual water supply disruptions mediated through the single family residential segment of the urban water sector. Water supply reductions in the single family residential segment accords with the typical policy response of policy-makers to water supply disruptions of the magnitudes examined here (10% to 30% shortage allocations).[1] In the welfare analysis presented in this paper our focus is on the effect of an annual water supply disruption, which involves rationing water during an annual hydrological cycle that is characterized by a rainy season (roughly October through March) and a dry season (roughly April through September) each year. On an annual basis, water supply disruptions tend to be concentrated on dry season residential water uses, for instance periodic limitations on outdoor landscape irrigation, because dry season rationing of residential household water uses selectively targets what policy makers consider to be the lowest-valued uses in urban water demand. However, the general welfare loss framework we describe in this article can be applied in the analysis of supply disruptions for different durations, seasons and places.

In a seminal paper on residential water demand, Renwick and Green (2000) [hereafter

[1]The cutback on urban water suppliers in California for the year 2015 is projected to be met through cutbacks in residential deliveries, with the bulk of the water restrictions applied to single family residential users.

RG] use utility-level panel data over the period 1989-1996 to estimate the price response of demand to water management policies for eight urban regions in California. We follow RG in framing our analysis around panel estimates of residential water demand in California; however, our analysis departs from their analysis in several essential ways. First, RG treat their panel data on utility-level water consumption and prices as a pooled cross-section, whereas we take advantage of the panel data structure to account for time-invariant characteristics, such as regional mean historical income and climate variables, that are correlated with both water prices and demand. Second, our study expands the cross-section of urban water demand observations from 8 regions to 37 independent rate-setting water utilities in the San Francisco Bay Area and Southern California. Given the high degree of intracluster correlation within water utilities, our panel technique has greater statistical power and allows for utility specific fixed effects. Third, RG estimate the average price response across utilities, while our methods allow us to consider heterogeneity in price elasticities by interacting price with household income. This addition is important, because our data are not only characterized by considerable heterogeneity in regional water rates, but also embody substantial differences in the responsiveness of water demand to price changes, leading to estimated price elasticities in the range between -0.10 and -0.24. Accounting for regional differences in water demand allows us to characterize the wide-spread distribution of welfare changes across space, particularly when the yardstick for losses is a baseline water equilibrium that is not allocatively efficient.

A naïve analysis of welfare changes due to shortages may consider marginal cost pricing and efficient rationing along a single, aggregate water demand function; however, because most water utilities set rates to recover a substantial portion of the fixed costs of water service, and the prevailing debt service varies across water utilities, the resulting water rates exhibit a substantial degree of heterogeneity across utilities. When welfare changes are measured from an initial allocation that does not equalize the marginal value of water across urban water consumers, water rationing will tend to alter these pre-existing distortions, especially if there is also variation in price responsiveness across urban water consumers. Indeed, welfare losses from water supply disruption can be tempered by rationing water in a manner that restores allocative efficiency. To illustrate the essential role of these features in calculating the welfare loss of a water supply disruption, we compare welfare losses under marginal cost pricing (P=MC) in a base scenario in which water utilities share a common price elasticity and initial price, a scenario in which water utilities have heterogeneous price elasticities and share a common initial price, and a scenario in which water utilities have heterogeneous price elasticities and initial prices; these are compared to a scenario in which welfare losses are calculated under average cost pricing (P>MC). Furthermore, we consider welfare losses under allocations that proportionally ration consumers in all regions and that ration consumers in a manner to equalize the marginal value of water across regions (what we refer to as "efficient rationing").

In summary, this article presents a framework for evaluating welfare losses from urban water shortages, taking into account local differences in demand characteristics and utility pricing structures. We use panel data from 37 urban water utilities in California over the period 1996-2009 to estimate utility-level price elasticities of residential water demand. We then use these estimates, coupled with information on rates and costs of service, to determine the welfare losses from a temporary water supply disruption for 53 urban water utilities in the San Francisco Bay Area and in Southern California. As context for our welfare results, the average price of water these utilities charge is $1232 per acre-foot. We find that average welfare losses due to a 30% supply disruption are approximately $2,300 to $2,500 per acre-foot of shortage in the case of marginal cost pricing for the volumetric rate; these estimates represent a lower bound on welfare losses since the volumetric rate usually carries a portion of the fixed costs. Therefore, a key result of the paper is that when we assume that volumetric rates also carry a portion of the fixed costs, then average welfare losses per acre-foot of shortage increase to approximately $3,500. A second finding of the paper is the large variation in shortage losses across water utilities, with losses from a 30% shortage varying from under \$1,000 per acre-foot of shortage to over \$12,000 per acre-foot.

The welfare results presented in the preceding paragraph were calculated under the assumption of proportional rationing across water utilities, which is not an allocatively efficient rationing scheme. Therefore, as a final exercise we compare welfare losses under a proportional rationing regime across water utilities to an efficient rationing regime that equates the marginal value of water across utilities. Naturally, we find that absolute welfare gains due to implementation of an efficient rationing regime in lieu of proportional rationing are increasing in the size of the regional supply disruption. In the San Francisco Bay Area gains are \$3.4 million and \$46.5 million for percent disruptions of 10% and 30%, respectively. In Southern California gains are \$38.0 million and \$116.7 million for percent disruptions of 10% and 30%, respectively. Similarly, we find that, in percentage terms, the welfare gains due to implementation off an efficient rationing regime relative to a proportional rationing regime can increase in the size of the regional supply disruption. Efficient rationing can reduce aggregate welfare losses relative to proportional rationing by an estimated 11.5% for a 10% regional supply disruption and by an estimated 15.9% for a 30% regional water supply disruption in the San Francisco Bay Area. However, this is not always the case; in Southern California we find that efficient rationing relative to proportional rationing reduces aggregate welfare losses by an estimated 13.3% for a 10% regional supply disruption but only 6.1% for a 30% regional water supply disruption. The short explanation for this counter-intuitive result is that the benefits of efficient rationing relative to proportional rationing can be broken into (i) a fixed benefit of achieving an efficient allocation under a zero shortage baseline and (ii) a variable benefit of efficient rationing corresponding to shortages of 10%, 20% and 30% that are beyond the fixed benefit. In percentage terms, the fixed benefit of efficiency gains when moving from proportional to efficient rationing is larger under a 10% shortage relative to a 30% shortage. Moreover, the variable benefit of efficiency gains when moving from proportional to efficient rationing increases more quickly in regions with inelastic demands compared to regions with relatively more elastic demands. This explains why we observe the contrasting results on efficiency gains in percentage terms between the San Francisco Bay Area (more inelastic) and Southern California (more elastic). In summary, the decline of efficiency gains in percentage terms when comparing efficient rationing relative to proportional rationing is surprising and results because the intial rates are allocatively inefficient and price responses vary across regions, which taken together, underscore the importance of accounting for heterogeneity in initial rates and price elastiticies across utilities.

From the policy perspective, we summarize three main points. First, properly handling fixed costs in the welfare calculation is essential for calculating economic losses for supply reductions. Second, losses under proportional rationing approximate losses under efficient rationing. This suggests a relatively moderate impact of accounting for regional differences in demand. Hence, it seems like aggregated analysis can serve as a good approximation for total welfare losses at a highly disaggregated level. Third, if understanding the pattern for the distribution of welfare losses is an objective of the analysis then accounting for heterogeneity in price elasticities and initial prices across water utilities is essential.

The remainder of the paper is structured as follows. The next section presents the conceptual model underlying our welfare loss framework. In Section 3, we describe the residential water demand estimation with a careful exposition of what we consider to be the main empirical challenges; we present our econometric specification; we describe the data used in the regression analysis; review the main regression results and consider several empirical checks to evaluate the robustness of our main findings. In Section 4, we walk the reader through the calculation of welfare losses due to a year-long water supply disruption for 53 urban water utilities in the San Francisco Bay Area and Southern California under different sets of assumptions about price elasticities, initial prices and how volumetric prices are set; we also discuss equity considerations under multi-tiered pricing structures and welfare losses under proportional versus efficient rationing rules. The final section concludes.

2 Welfare Loss Framework Under Average Cost Pricing

Our loss framework considers the effect of a year-long urban water supply disruption on ratepayers' welfare under existing infrastructure with no short-term adaptation. Water shortages relative to quantity-demanded under baseline prices following a supply disruption have the potential to adversely affect economic outcomes among several types of water users, including rural and agricultural users; however, we confine our analysis to the case of urban water management. Specifically, we consider a drought response framework for urban water utilities in which year-long water supply reductions of a given magnitude are mediated through the residential segment of the urban water sector. A drought response framework that primarily targets residential water use, for instance by imposing restrictions on outdoor irrigation, corresponds to the typical urban water management response to supply disruptions of relatively small magnitude and short duration.[2] For purposes of this analysis, we consider a year-long disruption to be a short duration given the large capital investments required. Water infrastructure could not respond quickly to a one-year supply disruption, nor do we expect technology development and/or broad adoption of residential water savings devices to occur in under a year.

We measure residential ratepayer welfare losses as the difference between the area under residential demand curve and the avoided cost of reduced water service (naturally, the variable costs of service delivery are not paid for on shorted units of water, where the number of shorted units is equal to the difference between consumption absent a supply disruption and consumption with a supply disruption). Given that a substantial portion of the cost of water service represents fixed cost, the vast majority of which is sunk, our methodology is more appropriate than the standard consumer surplus measure. Specifically, our measure of the ratepayer welfare loss is reconciled with the consumer surplus measure when the avoided

[2] We note that urban utilities with agricultural customers may choose to ration them before residential customers. However, it is rare for the urban utilities in our data set to have agricultural customers and when they do it is small share of their customer base. Further, agricultural customers may be served by non-potable water supply sources; thus, the choice to ration residential customers first would not be affected.

cost of reduced water service is described by a constant unit cost function at the prevailing residential water rate, but differs, often substantially, from the consumer surplus measure under circumstances in which residential water rates exist primarily for fixed cost recovery (e.g. a marginal cost of service delivery at or very close to zero).

2.1 Evidence of Average Cost Pricing

We offer two pieces of evidence to support our claim that residential volumetric water rates exist primarily for fixed cost recovery. Our first piece of evidence is in Table 1 which presents the distribution of average prices across water utilities used in the regression analysis. The distribution ranges from an average of \$1.26 per hundred cubic feet (ccf) in Anaheim to an average of \$8.16 per ccf in Skyline Water District. While each water utility has its own separate supply portfolio, all of the water utilities listed from the San Francisco Bay Area receive a large share, if not, all of their supplies in the form of imported surface water via the Regional Water System (RWS) administered by the San Francisco Public Utilities Commission and serviced by the Hetch Hetchy Reservoir. The marginal costs of delivering these RWS supplies should be similar across water utilities. The fact that we observe widely different prices across utilities reflects that each utility packages fixed costs into their volumetric rates differently. This can occur due to the different levels of fixed costs each utility incurs and the wide variance in the numbers of customers served (e.g Alameda has 71,000 single family residential accounts while Westborough only has 3,701 single family residential accounts (BAWSCA, 2012)). Our second piece of evidence is based on public financial records indicating that a large portion of the volumetric rates reflect capital expenses and debt service. For example, a public document from the San Francisco Public Utilities Commission from February 2015 (SFPUC, 2015) indicated that approximately half of their current volumetric rate reflects capital investments and debt service for capital investment projects. These estimates do not reflect administrative and labor operating expenses which are mostly fixed and large in magnitude so that fixed costs may constitute considerably more than half of the volumetric rate (SFPUC, 2014).

Similarly, financial documents from the Metropolitan Water District of Southern California show that annual operating expenses between FY 2009-2010 through FY 2011-2012 do not vary significantly with changes in water deliveries (MWDSC, 2013). We use this data to estimate a marginal cost of service delivery in Southern California to be $193 per acre-foot. To be sure, the marginal costs of water delivery will vary across utilities due to differences in factors such as power costs associated with conveyance and water treatment costs; however, as a first approximation we expect these variable costs to be similar for water utilities in the San Francisco Bay Area as they share a common water supply source in the RWS. Likewise, we expect variable costs to be similar for water utilities in Southern California as they share common water supply sources and distribution via the Metropolitan Water District of Southern California. It is worth noting that the conveyance costs, which depend on distance and topography, is likely higher for water delivered to Southern California from afar than for water delivered to the San Francisco Bay Area via gravity flow from Hetch Hetchy Reservoir, which are relatively close together. In addition, the very high quality of Hetch Hetchy Reservoir water delivered to the San Francisco Bay Area keeps water treatments costs low. Thus, we might expect the marginal costs of service delivery in the San Francisco Bay Area to be less than $193 per acre-foot, which is calculated based on data from Southern California. Ultimately, there are no accurate records available on the marginal costs of service delivery, though in our view there is clear evidence to suggest that the marginal costs are not equal to the prices charged to consumers. In subseqent analysis we will provide bounds for our estimates of average welfare losses per acre-foot of shortage by assuming marginal costs equal to the volumetric rates charged to end-users (lower bound on average welfare losses) and then present an estimate that assumes the marginal costs are much closer to zero (a marginal cost equal to zero would result in an upper bound on average welfare losses). Given this, our approach underscores the important insight that the method of financing by a water utility, for instance the extent to which fixed costs are recovered through fixed charges per household meter rather than through volumetric prices for water, is essential for calculating ratepayer welfare losses.

2.2 Measuring Welfare Losses

Measurements of ratepayer welfare losses are determined by both the magnitude and duration of the water supply disruption. Following Brozovic, Sunding, and Zilberman (2007), we define the severity of the water supply disruption in region i at time t as $z_{it} \in [0,\ 1]$, where $z_{it} = 0$ corresponds to a complete outage and $z_{it} = 1$ corresponds to the baseline level of service.

Let $f_{it}(z_{it})$ denote the probability density function of residential water disruption z_{it} in region i at time t and let $W_i(z_{it})$ denote consumer willingness-to-pay to avoid a supply disruption z_{it} in region i at time t. For a period of duration T until baseline water service is reestablished, consumer willingness-to-pay in the residential (R) sector to avoid a cumulative service disruption across I regions and T periods is given by:

$$W^R = \sum_{t=1}^{T}\sum_{i=1}^{I}\int_0^1 W_i(x) f_{it}(x)dx \tag{1}$$

with x as the variable denoting the values z_{it} can assume. For a given region and time, the computation of $W_i(z_{it})$ involves integrating the area under a demand curve for a supply disruption level of z_{it}. Specifically, willingness-to-pay to avoid a supply disruption of magnitude z_{it} in region i at time t can be defined as:

$$W_i(z_{it}) = \int_{Q_i(z_{it})}^{Q_i^*} P_i(x)dx \tag{2}$$

where $P_i(Q_i)$ is the (inverse) demand function for residential water in region i, $Q_i^* = Q_i(z_{it} = 1)$ is the baseline quantity of water delivered to residences in region i prior to a supply disruption, and $Q_i(z_{it})$ is the quantity of supply available after a water supply disruption in region i at time t.

Consumer willingness-to-pay to avoid a (contemporaneous) water supply disruption of a given magnitude in equation (2) is calculated for each region by constructing an aggregate demand curve to represent the residential water segment. For utilities with a uniform pricing structure, $P_i^* = P_i(Q_i^*)$ is the volumetric rate paid by residential homeowners under baseline conditions prior to the water supply disruption in region i. For regions with an increasing block pricing (IBP) structure, P_i^* is the marginal rate paid by a representative residential consumer in region i corresponding to the tier on which the last unit of household water consumption occurred. Integrating losses in equation (2) over the probability distribution of outcomes and the duration of the water supply disruption results in the measure described by equation (1).

Ratepayer welfare losses that result from water supply disruption in a given market are mitigated to the extent that delivering a smaller quantity of water reduces the system-wide cost of water service. The ratepayer welfare loss that occurs in region i following a water supply disruption is therefore the difference between the measure in equation (1) and the avoided cost of service. If water service is characterized by constant unit cost at the prevailing baseline price level, P_i^*, then the avoided cost of service is $P_i^*(Q_i^* - Q(z_{it}))$, and the ratepayer welfare loss following a water supply disruption of a given magnitude reduces to the usual consumer surplus triangle.

As we have discussed, for most water utilities, the cost of water service includes a large fixed cost component for elements of the water distribution network related to infrastructure, repair and maintenance of water lines, metering service, and public administration. To the extent that fixed costs facing water utilities are sunk, the avoided cost of water service corresponds to the reduction in variable cost in region i for the duration of the water supply disruption. The variable cost of water supply include the energy and chemical costs of treating water, and conveyance and distribution costs, and the avoided cost of water service encompasses the reduction in these variable cost components in response to reduced water deliveries.

The avoided cost of service depends on the water portfolio of a given region and on the distribution of the water supply disruption across water sources within the portfolio. A disruption of relatively high-cost imported water supplies would entail a larger avoided cost of service component than a disruption of local water supplies by more greatly reducing procurement costs of water in the system. Given the variation in the water portfolios of water utilities in California, the avoided cost of service for units of water no longer delivered in response to a residential supply disruption likely varies across space.

Let $c_i(z_{it})$ denote the avoided unit cost of service in region i at time t. Accordingly, the contemporaneous ratepayer welfare loss in region i of a given magnitude water supply disruption is given by:

$$L_i(z_{it}) = \int_{Q_i(z_{it})}^{Q_i^*} P_i(x) - c_i(x)dx. \tag{3}$$

Once again, notice that the contemporaneous welfare loss in equation (3) corresponds with a consumer surplus measure in the case where $c_i(z_{it}) = P_i^*$. In this case, equation (3) reduces to:

$$L_i(z_{it}) = \int_{Q_i(z_{it})}^{Q_i^*} P_i(x)dx - P_i^*(Q_i^* - Q(z_{it})). \tag{4}$$

The expression for losses in equation (4) is a lower bound on the economic loss experienced by ratepayers and corresponds to the case of marginal cost pricing. For a period of duration T until baseline water service is reestablished, the ratepayer welfare loss in the residential (R) sector resulting from a cumulative service disruption across I regions and T periods is given by:

$$L^R = \sum_{t=1}^{T}\sum_{i=1}^{I}\int_0^1 L_i(x)f_{it}(x)dx \tag{5}$$

where $L_i(z_{it})$ is defined in equation (3).[3]

[3] We note that L^R represents aggregrate expected losses across I regions between the current period and period T, which reflects the value of a perfectly reliable supply.

In this article we simplify the welfare analysis be calculating contemporaneous ratepayer welfare losses for one period, where a period is defined to be one year (seasonal pricing is not common among the water utilities considered). This approach is assumed since quantity demanded is observed at the annual time-step. In the next section, we describe our econometric methods for estimating regional demand functions. The ratepayer welfare loss from a water supply disruption is then calculated using the loss measure (5) and regional estimates of demand conditions facing water utilities in the San Francisco Bay Area and in Southern California.

3 Residential Water Demand Estimation

The estimation of the price elasticity of water demand is essential for determining ratepayer welfare losses during a supply disruption. We estimate the price elasticity of average single family residential annual water demand using data on annual consumption and the number of accounts in the single family residential sector.[4] In a naïve demand estimation presented one might regress quantity on marginal price, which allows us to interpret the coefficient on marginal price as the price elasticity of demand when both quantity and marginal price are in logarithmic form and demand is isoelastic. The corresponding regression equation is:

$$\ln(q_{it}) = \beta_0 + \beta_1 \ln(p_{it}) + \eta_{it} \tag{6}$$

where q_{it} is quantity and p_{it} is marginal price for utility service area i in year t. This regression specification for demand is complicated due to several sources of potential bias, we discuss each in turn.

An immediate concern with the specification in equation (6) is simultaneity bias due to contemporaneous market price and demand shocks. However, in our sample and in California more generally, prices are set by local government administrators as opposed to market

[4] Annual level consumption data is used as comprehensive consumption data is not available for our analysis at the daily or monthly levels.

forces. Like Olmstead (2009), we argue the demand estimation does not suffer from this form of simultaneity bias. Further, one may address annual demand shocks common to all water utilities with the inclusion of year fixed effects. Another concern with equation (6) is that the data are treated as a cross-section (instead of taking advantage of its panel aspect), which may generate omitted variable bias due to excluding unobserved time-invariant characteristics. For example, there may be an inherent degree of conservation effort within each water utility service area, which would be negatively correlated with consumption. It is possible that the degree of conservation within a water utility service is negatively or positively correlated with price; either correlation would result in omitted variable bias. We address this by including utility fixed effects, which is similar to the strategy in Olmstead, Hanemann, and Stavins (2007) who use city fixed effects to address the form of omitted variable bias described above. Additionally, in cross-sectional analysis we see that characteristics such as household income and derived demand factors such as lot size are positively correlated with consumption and price. These demand factors are relatively slow to change during our study window so including utility fixed effects should largely control for these factors.

A separate source of potential simultaneity bias is that many water utilities use increasing block price (IBP) schedules so that the marginal price increases as consumption increases; thus, price is dependent on own consumption. The endogeneity issue introduced by IBP schedules is well-documented in the in labor supply and income taxation literature (Auten and Carroll, 1999; Saez, Slemrod, and Giertz, 2012; Ziliak and Kniesner, 2005; Hewitt and Hanemann, 1995). An alternative would be to use average price, but that is also endogenous to changes in quantity by construction. To avoid the simultaneity issue introduced by making the price measure an explicit function of consumption, we choose price on the median tier of each utility (by year) to be our price measure. This breaks the consumer's co-determination of marginal price and consumption because the administrator determines the median tier price. In addition, we instrument for our price measure using a method similar to that described by Olmstead (2009) to decouple price from consumers' choice of block. The approach also has the benefit of helping address measurement error, which we turn to next.

The median tier price mis-measures the expected marginal price consumers anticipate paying, which results in attenuation bias. Following Alberini and Filippini (2011) we address this errors-in-variables problem by instrumenting the median tier price with lagged prices. In particular, we use a set of instruments consisting of the the lagged price on each tier of the IBP schedule. This is similar to Olmstead (2009) who instruments marginal price with the price on each tier of the IBP schedule and the fixed fees in order to break the simultaneity between own-price and consumption. In our setting we limit our instruments to the lagged prices on each of the first four block tiers since more than 80% of the utilities in the regression data have four or fewer price blocks. If a water utility has a uniform price schedule, then we re-define it to be an IBP schedule with four tiers each having the same price. Similarly, if a water utility has two or three block tiers, then we re-define them to be IBP schedules with four tiers with the last three or two tiers having the same price (i.e., the price on the second or third tier depending on whether the water utility has a two block or three block price schedule). We do not have comprehensive data on fixed access fees so are not able to include these as instruments.

A separate form of attenuation bias may result because our sample consists of both water utilities with uniform volumetric pricing and IBP schedules. Olmstead, Hanemann, and Stavins (2007) show that the price elasticity of demand may depend on price structure. In their theoretical analysis, they find that IBP schedules can have off-setting effects so that the issue of how IBP schedules affect the price elasticity is ultimately an empirical one. In their empirical analysis, they find a dampening effect of IBP schedules on the estimated price elasticity of demand. The intuition is reflected in Figure (1), which depicts a demand curve that lies on a kink point of the IBP schedule; increases or decreases on the corresponding adjacent block tiers may not affect the optimal consumption point at all. That is, for some households there will be no price response. As can be seen in Table 2, this is a concern for our analysis since our regression data is approximately split between utilities using uniform pricing and IBP schedules. We conduct a robustness check to test for this source of bias by interacting our price measure with an indicator for whether the utility uses an IBP schedule.

A final concern is that of omitted variable bias due to excluding unobserved time-variant conservation effort and heterogeneous characteristics. The inclusion of utility fixed effects controls for time-constant differences in their constituents, though given the long period of data and the large changes in pricing across water utilities and within water utilities during the study period, the research design is vulnerable to bias due to time-varying unobservables. Of particular concern are utility-specific conservation efforts that have become more frequent and intense over the study period, but have rolled out differently across water utilities. If utility-specific roll-outs of conservation efforts coincide with rate increases, then we have a time-varying omitted variable that would be positively correlated with price and negatively correlated with consumption. Omission of such a time-varying factors would result in downward bias for our estimator of the price elasticity. To address this concern we propose two tests.

First, we propose a model with county-specific linear and quadratic time trends. Including county-specific time-trends accounts for unobserved factors that share a common trend within a county over time. In theory, these can account for time-varying unobserved conservation efforts occuring at the county level. While the county-level does not coincide with the administrative level of a water utility, it is the case that water utilities sharing a common region tend to support similar conservation efforts. For example, in Southern California utilities experienced a common "Be Waterwise." campaign in recent years; similarly, the 26 utilities belonging to the Bay Area Water Supply & Conservation Association (BAWSCA) have shared conservation efforts.[5]

As a separate check, we propose an interaction between our price measure and a drought indicator variable that denotes whether an observation occurs in the 2007 through 2009

[5]For examples, see their conservation web page: http://bawsca.org/conservation/.

drought period, a period of time during which price increases may have closely coincided with increased conservation efforts. Omitting conservation efforts that are correlated with within utility price movement would result in a changing price elasticity over time if conservation efforts and price increases are more closely related in the more recent period.[6] Thus, if the coefficient on the interaction term between price and the drought indicator is not distinguishable from zero then we have some evidence consistent with there being limited bias introduced by omitting utility-specific time-varying unobserved factors such as conservation efforts.[7] If the drought indicator is distinguishable from zero, then this suggests that bias of the sort we describe could exist although such a finding would also be consistent with a changing price elasticity.

3.1 Econometric Specification

Our basic fixed effects estimating equation is:

$$\ln(q_{it}) = \beta_1 \ln(p_{it}) + \beta_2 W_{it} + \mu_i + \tau_t + \epsilon_{it} \tag{7}$$

where q_{it} is the single family residence average monthly consumption for utility service area i and year t; p_{it} is the price per ccf on the median tier of the price schedule; W_{it} is a vector of precipitation and temperature measures; μ_i is a utility fixed effect; τ_t is a year fixed effect; and ϵ_{it} captures all unobserved factors affecting the dependent variable. This specification will control for all unobserved time-invariant utility specific characteristics.

As previously described, simultaneity and attenuation bias are potential problems with the specification in equation (7) because median tier price may (i) be endogenous as utility administrators may have set the rate structure in anticipation of current demand; (ii) be

[6] This is true unless utility-specific time-varying conservation efforts across utilities have opposite correlations with their within utility price, in which case, the price elasticity may not change over time.

[7] We perform similar tests by lengthening the window of our indicator variable for the latter years of our data. That is, we re-define our indicator variable to denote the period between 2006 and 2009 and re-estimate the model; then re-define our indicator variable to denote the period between 2005 and 2009 and re-estimate our model; and continue in a similar fashion until our indicator denotes the period between 1997 and 2009.

endogenous due to the consumer's co-determination of quantity and price; and (iii) mis-measure the consumer's expected marginal price. We have already discussed reasons why our estimator for the price elasticity is less vulnerable to the simultaneity biases of (i) and (ii). An instrumental variables estimation can eliminate attenuation bias due to mis-measured consumer's expected price and may also address bias due to (i) and (ii). As instruments we use one-year lagged prices from each of the first four tiers of the IBP schedules (again, for uniform pricing we assume an identical price for each tier). Our preferred estimating equation becomes:

$$\ln(q_{it}) = \beta_1 \widetilde{\ln(p_{it})} + \beta_2 W_{it} + \mu_i + \tau_t + \xi_{it} \tag{8}$$

where $\widetilde{\ln(p_{it})}$ is $\ln(p_{it})$ instrumented with each $\ln(p^k_{i,t-1})$ of four tiers where k denotes the tier number (1-4) in the first-stage regression equation:

$$\ln(p_{it}) = \sum_{k=1}^{4} \gamma_k \ln(p^k_{it-1}) + \gamma_5 W_{it} + \delta_i + \phi_t + \nu_{it} \tag{9}$$

The lagged prices on each of these four tiers are predetermined and hence exogenous in the time series sense. The drawback of this measure is, if there are few changes in the median tier price, the instrument might be invalid as it does not break the correlation of the current median price with the structural disturbance. However, the standard deviation of the within utility mean price is 82 cents which is approximately 35% of the average price ($2.35 per ccf) observed in our sample. In the next section we show additional evidence that there is significant variation across time in the median price.

Finally, to account for heterogeneity in the price elasticity across water utilities we interact our price measure with the median household income of the utility's service area. This is consistent with Reiss and White, (2005) who find that the price elasticity of electricity demand becomes more inelastic as household incomes increase. In the urban water literature Mansur and Olmstead (2012) estimate price elasticities that depend on household characteristics including household income and lot size.

3.2 Data

The price elasticity of demand for water is estimated using single family residential median tier price and annual consumption data from urban water utilities in the San Francisco Bay Area and in the Metropolitan Water Disctrict of Southern California (MWD). Annual consumption and median tier prices for water utilities in the San Francisco Bay Area were recorded from the Bay Area & Water Supply Conservation Agency Annual Surveys from 1996-2009; similar data for water utilities in the MWD service area was obtained by directly contacting each individual water utility. The final sample of utilities used to estimate our econometric model includes 27 utilities from in the San Francisco Bay Area and 10 utilities from within the MWD service area. In total, the sample contains 453 observations spanning 37 water utilities.

Average single family household annual consumption levels for each water utility was calculated by dividing the total single family residential consumption level (net of systems losses) for the fiscal year by the number of single family residential accounts for that fiscal year. The equilibrium price of water for the typical user in each region was assumed to be equal to the price per ccf on the median tier of the utility's IBP schedule.[8] A utility specific servic area measure of median household income is generated by intersecting utility specific borders with the year 2000 Census tract borders, and calculating a household weighted-average of median household income. Table 1 presents summary statistics of price and average monthly household consumption by utility. Notably, the median within utility standard deviation of price is approximately $0.50 per ccf (with an unweighted average price of $2.39 per ccf), which provides evidence in support of the utility fixed effects research design.

[8]In our dataset season pricing of water is not at all common. The City of Pasadena is an exception, though they charge only $0.01-$0.07 per ccf more during the summer months (depending on the tier) relative to non-summer months.

3.3 Estimation Results

Table 3 presents the results for alternative specifications of the empirical model. In column (1) we present a simple cross-sectional specification with ln(Price), weather controls, and year fixed effects. We observe a positive elasticity, which suggests that the specification is not accounting for variables correlated with both price and consumption. As a first step to address potential omitted variable bias we estimate our basic estimating equation shown in equation (7), which adds utility fixed effects to the estimation reported in column (1). Under this specification, which is reported in column (2) of the same table, we obtain a precisely estimated elasticity of -0.100; an estimate that is smaller than found in previous studies. In column (3) we run the same specification as is presented in column (2) except that we instrument for price with lagged prices from the first four tiers of each utility's IBP schedule in order to address measurement error in price and simultaneity bias due to own-consumption; the point estimate changes to -0.143. We note that one-year lagged prices from the first four tiers on the IBP structure explains variation in median tier price; the F-statistic of the excluded instruments is 41. The estimated elasticity is generally consistent with other estimates in the academic literature (Nataraj and Hanemann, 2011), although is still somewhat inelastic (Klaiber et al., 2014; Olmstead, Hanemann, and Stavins, 2007). Column (4) of Table 3 is identical to the specification in column (2) except we have introduced heterogeneity into the price elasticity by interacting price with income. We observe that there is statistically significant variation in the price elasticity according to income.

Our preferred specification is an instrumental variable specification with utility fixed effects and an interaction between ln(Price) and l(Income), which is reported in column (5). The inclusion of utility fixed effects addresses omitted variable bias introduced by utility-specific unobserved time-invariant characteristics. Instrumenting median tier price with lagged prices from each of the tiers removes attenuation bias due to measurment error and will also remove simultaneity bias due to own-consumption if the lagged prices from each tier are only related to current consumption through their direct effect on current median tier price. The inclusion of the interaction term between median tier price and median household income permits us to statistically detect the existence of utility-level variation in average price responsiveness based on a measure of household income. Using the results reported in column (5) a water utility with an average household income of $75,000 (approximately the average household income observed across water utilities included in the regression analysis) would have an estimated elasticity of -0.149.

3.4 Robustness Checks

In Table 4 we consider a series of robustness checks to evaluate the sensitivity of our results. For ease of presentation and interpretation, we do not present results for specifications including the interaction term between price and income. One concern, described by Olmstead, Hanemann, and Stavins (2007), is that pooling utilities using uniform and IBP schedules into one regression will result in a form of attenuation bias. This form of bias could result because households with demand curves such as depicted in Figure 1 will, from a theoretical perspective, not respond to relatively small price changes. If there are many such households then this would act to bias our estimator for the price elasticity towards zero. In column (1) of Table 4 we consider whether utilities with increasing block pricing schedules have a different price elasticity than those using uniform pricing. The point estimate on the interaction term between ln(Price) and an indicator variable (IBP) denoting that the utility uses an IBP schedule is 0.002 and is not statistically significant from zero. This is evidence that for our sample, pooling utilities using uniform and IBP schedules is not dampening the price elasticity.

A second concern is that of omitting a time-varying demand factor that is correlated with price. In theory, our IV estimation should address this concern; however, there is the possibility that lagged prices are correlated with conservation effort via lagged conservation effort. One test to evaluate the existence of this bias is to include region-specific time trends to account for unobservable region-specific trends such as conservation efforts that may be biasing our estimator for the coefficient on price. We add county-specific time trends to our model and re-estimate the price elasticity. In column (2) of Table 4 we observe that the estimated price elasticity under this specification is slightly more inelastic, though a test on this point estimate (-0.126) compared to that in column (3) of Table 3 (-0.143) indicates no statistically significant difference. While this does not rule out bias due to omitting time-varying factors such as conservation efforts, the results are consistent with a limited form of such bias.

As a separate test for this form of omitted variable bias, we generate an indicator variable (Drought_t) denoting whether an observation is post the start of the year 2007 drought, which includes the years 2007, 2008, and 2009 in our sample, and then interact Drought_t with our price measure. If the point estimate on the interaction term between ln(Price) and Drought_t is 0.014 and is not statistically significant from zero. This is evidence that for our sample, the estimated price elasticity is not different during the designated drought period relative to the pre-drought period. This is consistent with the existence of limited bias in our estimator for the price elasticity due to coincident increases in conservation efforts and prices during the drought period.

A related concern is that the price elasticity of demand is dynamic, and thus, changing over time. In results not shown, we re-define the drought indicator variable to allow for an arbitrary structural break in the price elasticity. For example, we define an indicator variable $Post96_t$ that assumes a value of zero for all observations prior to the year 1997 and a value of 1 for all years post 1996, interact this indicator variable with our price measure, and re-estimate the model corresponding to the results presented in column (3) of Table 4. We repeat this estimation by re-defining a similar indicator variable for each year in the study period (e.g. we define $Post97_t$ to assume a value of zero for all years prior to the year 1998 and a value of 1 for all years post 1997). Results are all qualitatively similar to the point estimate reported in column (3) of Table 4 and suggest no structural break in the price elasticity over our study window.

4 Welfare Losses from Water Supply Disruptions

In this section, we describe the estimation of welfare losses for parts of Northern and Southern California from an annual residential water supply disruption. First, we parameterize the welfare loss function and solve for an expression to point out the key contributions of this paper. Next, we describe the data used to conduct welfare analysis for 53 urban water utilities, which is separate from the data on 37 utilities used in the regression analysis. We follow with a presentation for our estimates of the average welfare losses per acre-foot of shortage and discuss the roles of heterogeneity in price elasticities, initial rates and the extent to which fixed costs are bundled into volumetric rates. We separately estimate aggregate and average welfare losses for the San Francisco Bay Area and Southern California to illustrate the distributional impacts across space of these three sources of heterogeneity. We also include a discussion of equity considerations under IBP schedules. Finally, we estimate and discuss the allocative inefficiency of applying proportional versus efficient rationing across utilities during times of regional supply disruptions. A puzzling finding is highlighted and explained using contrasting results from the San Francisco Bay Area and Southern California.

4.1 Parameterizing the Loss Function

We assume a constant elasticity of demand specification:

$$P_i = A_i Q_i^{\frac{1}{\varepsilon_i}} \tag{10}$$

for $i = 1,..., n$, where ε_i is the price elasticity of water demand in region i and A_i is a constant. Let P_i and Q_i^* respectively denote the retail water price and quantity of water consumed by residential households in region i under baseline conditions. For a given water supply disruption with an available level of water given by $Q_i(z_{it}) < Q_i^*$, it is helpful to define the relationship between these quantities in terms of the percentage of water that is rationed in region i at time t, r_{it}, as:

$$Q_i(z_{it}) = (1 - r_{it})Q_i^*. \tag{11}$$

Making use of equations (3), (4), (10) and (11), the welfare loss following a supply disruption of magnitude z_{it} in region i at time t can be calculated from equation (3) as:

$$L_i(z_{it}) = \frac{\varepsilon_i}{1+\varepsilon_i} P_i^* Q_i^* [1 - (1 - r_{it})^{\frac{1+\varepsilon_i}{\varepsilon_i}}] - \int_{Q_i(z_{it})}^{Q_i^*} c_i(x)dx. \tag{12}$$

Under the assumption of a flat marginal cost curve, we can re-write (12) in terms of average loss per unit of shortage:

$$L_i/(Q_i^* \cdot r_{it}) = \frac{\varepsilon_i}{1+\varepsilon_i} P_i^* [1 - (1 - r_{it})^{\frac{1+\varepsilon_i}{\varepsilon_i}}]/r_{it} - c_i \tag{13}$$

where c_i is a constant per unit variable cost. Equation (13) makes clear that conditioned on a supply disruption r_i, the welfare implications of a supply disruption in a particular region depends on heterogeneity in (i) price elastitices, (ii) initial prices and (iii) the variable cost of water service, where (ii) and (iii) provide insight into the extent to which fixed costs are bundled into volumetric rates.

4.2 Data for Calculation of Losses

Using equation (13) losses are calculated for 53 urban water utilities including 27 utilities in the San Francisco Bay Area; and 26 utilities in Southern California. The resulting utility-level welfare impacts are aggregated to calculate the welfare losses in parts of Northern and Southern California.

Welfare losses depend on regional prices, baseline quantity demanded, the supply disruption, the price elasticity of demand and the marginal cost of service delivery. Estimates for all of the information required for the loss calculation are publicly available except for the price elasticity of demand and the marginal cost of service delivery. Baseline single family residential demand data is obtained through the Bay Area Water System and Conservation Association (BAWSCA) Annual Survey from FY 2009-2010, and from estimates provided by SFPUC and MWD. For the San Francisco Bay Area utilities belong to BAWSCA, the price data is the year 2009 median tier rate reported in the BAWSCA survey; prices for the other utilities are obtained from their websites or through a telephone interview. In the case of wholesale utilities, such as many of the utilities belonging to the MWD, no single median tier price exists because they sell their water to multiple local utilities who set their own rates. Thus, for each wholesale utility we collect rate information on every single local utility within the wholesale utility, and then calculate a quantity-weighted average of the median tier price. We present the range of median tier prices (converted to price per acre-foot of water) for these 53 urban water utilities in Table 5.

The demand estimation suggests that the price elasticity of water is significantly different across utilities throughout the state. Based on the results of column (5) in Table 3, we estimate a separate price elasticity for each of the 53 utilities considered in our welfare analysis. The range of elasticities is displayed in Table 5.

In terms of the residential loss functions, the impact of regional price elasticity values is to raise welfare losses from water service disruptions when demand is relatively inelastic and to lower economic losses in regions where demand is more elastic. Predictions of residential water supply disruptions in California are wide-ranging; thus, we consider water supply disruptions of 10%, 20%, and 30% when we evaluate losses due to a supply disruption.

The welfare analysis also requires information on the marginal cost of service delivery. We consider how operating expenses vary with water sales to recover a marginal cost of service delivery of \$193/AF. This is based water sales data reported in The Metropolitan Water District of Southern California Annual Report 2013 and operating expenses data reported in The Metropolitan Water District of Southern California Basic Financial Statements for the years that ended June 30, 2013 and 2012 and the same document for the years that ended June 30, 2012 and 2011. Admittedly, this is a rough approximation of the marginal cost of service delivery; the true marginal costs of service delivery will vary depending on the supply source and would account for variation in system losses. Nonetheless, a marginal cost of \$193/AF is consistent with our understanding that water utilities use some form of average cost pricing. Given that the price of residential water is generally greater than \$1,000/AF, this suggests that a large portion of the median tier prices residential consumers face is likely intended to recover fixed costs.

4.3 Average Welfare Losses Per Acre-foot by Scenario and Percent Disruption

Let us consider a back-of-the-envelope calculation of welfare losses associated with 10%, 20% and 30% shortages in the single family residential sector based on an estimated price elasticity of -0.189 (the weighted average of elasticities reported in 5), a common price across of \$1,232 per acre-foot (the weighted average of prices reported in 5) for utilities and the assumption that water rates reflect marginal costs of service delivery (P=MC). Using equation (13), these percent shortages correspond to estimated welfare losses of \$425, \$1,113 and \$2,319 per acre-foot of shortage, which are reported in the first row of Table 6. In the subsequent rows of Table 6, we will consider the welfare implications of heterogeneity across utilities in (i) price elastitices, (ii) initial water rates and (iii) the relationship between water rates (reflecting fixed costs) and the marginal cost of water service.

Under Scenario 1 we calculate the average welfare loss per acre-foot (quantity weighted) across the 53 urban water utilities under heterogeneous price elasticities, a common price and when the volumetric rates charged to end-users are assumed to only reflect marginal costs. We observe estimated welfare losses of \$438, \$1,169 and \$2,508 per acre-foot of shortage corresponding to shortages of 10%, 20% and 30%, which are similar to the results of the Base scenario. Immediately underneath these estimates, we report the standard deviations of average welfare losses per acre-foot across utilities which clearly illustrate how the back-of-the-envelope estimate misses the distributional effects of how shortages affect ratepayers. Moreover, reporting the results in terms of average welfare losses belies the extent of allocative inefficiency of proportional rationing in the presence of heterogeneous price elasticities; the standard deviations of the marginal welfare losses (compared to the standard deviations of average welfare losses) will naturally be larger.

Under Scenario 2 we calculate the average welfare losses per acre-foot (quantity weighted) across the 53 utilities under heterogeneous price elasticities and prices when the volumetric rates charged to end-users are assumed to only reflect marginal costs. Again, we observe estimated welfare losses of $418, $1,114 and $2,387 per acre-foot of shortage corresponding to shortages of 10%, 20% and 30%, which, like the Scenario 1 results, are similar to those of the Base scenario. However, the standard deviation of average welfare losses per acre-foot suggests even greater dispersion in average welfare losses across utilities than is reported for Scenario 1; likewise, there will be much greater dispersion in the implied marginal value of the last unit of shorted water across utilities.

We point out that the results reported for Scenario 1 and 2 are both likely under-estimates of the true welfare losses because they ignore that the volumetric rates of water utilities usually include a substantial portion of the fixed cost, which varies across urban utilities. In the most liberal interpretation, the numbers reported in Scenario 1 and Scenario 2 are lower bounds on the true magnitude of average welfare losses. Scenario 3 reports the average welfare loss per acre-foot (quantity weighted) across the 53 utilities under heterogeneous price elasticities, prices and heterogeneity in how the volumetric rates charged to end-users reflect both marginal costs and a portion of fixed costs. We observe estimated welfare losses of $1,458, $2,153 and $3,426 per acre-foot of shortage corresponding to shortages of 10%, 20% and 30%, which are significantly larger than the welfare results for scenarios that do not assume some form of average cost pricing. The results of Scenario 3 assume that the marginal cost of service delivery is $193 per acre-foot across urban utilities. While this is a strong assumption, it is clear that there is variability in the level of fixed costs, which are added into the volumetric rates by virtue of the dispersion in prices. This discussion highlights the fact that under average cost pricing, which is often employed by public water utilities, the willingness-to-pay to avoid a supply disruption is considerably greater than the usual consumer surplus triangle.

4.4 Equity Considerations Under Increasing Block Pricing Structures

The case of identical own-price elasticity of demand for all households within a common utility and proportional rationing of all pricing tiers during a water shortage accords with circumstances in which individual water utilities raise the price of each tier symmetrically by a constant percentage; this corresponds to the foregoing welfare analysis. However, under a multi-tiered pricing structure for retail water deliveries, such as IBP, the analysis of the welfare effects of supply rationing may be more complicated. The reason is that each new tier that is introduced in a pricing structure adds an additional degree of freedom in how a water utility can meet the supply constraint. For instance, with a two tiered pricing structure (e.g., Tier I and Tier II), a water utility can independently ration: (i) low demand consumers in the market by raising the price of Tier I water without altering the price of Tier II water; (ii) consumers with intermediate levels of demand by reducing the quantity of water that qualifies for the Tier I price; or (iii) high demand consumers in the market by raising the Tier II price. Different combinations of these activities result in different welfare implications and there is some variation in implementation in practice. For example, shortage year rates instituted by the Los Angeles Department of Water and Power (LADWP) in 2009 combine all three rationing methods, imposing a 15% decrease in the Tier I allotment of each household (from 28 ccf to 24 ccf in a 2-month cycle), a 15% increase in the Tier I rate (from $2.976 to $3.422 per ccf), and a 55% increase in the Tier II rate (from $3.53 to $5.48 per ccf). This policy would have minimal welfare implications for low-demand households already consuming less than 24 ccf per billing cycle, while raising the marginal water rate by 55% for users above

28 ccf per billing cycle and by 84% (from \$2.976 to \$5.48 per ccf) for users between 24 and 28 ccf per billing cycle.

One argument for this type of differential rate increase across tiers in a shortage year is equity if lower income households tend to consume on lower tiers compared to higher income households. However, if equity constraints are imposed then actual welfare losses would be larger in cases where water rates rise by larger percentages in higher tiers than in lower tiers, as in the case provided above for LADWP.[9] In this sense the welfare estimates presented in the preceding and forthcoming sections may be under-estimates of welfare losses experienced during a shortage.

4.5 Comparison of Results for Northern and Southern California

To better understand the regional patterns of the welfare losses in Table 6 we consider aggregate welfare losses in urban parts of Northern and Southern California. In the first row of each panel in Table (7) we present estimates of the total losses that may be experienced by the single family residential sector in Northern and Southern California assuming the marginal cost of service delivery is \$193 per acre-foot (see earlier discusion in Section 2.1 for justification). For the San Francisco Bay Area (Northern California) utilities considered, total losses are estimated to be \$29 million to \$288 million under disruptions of 10% to 30%. For the Southern California utilities total losses are estimated to be \$285 million to almost \$2 billion under disruptions of 10% to 30%. Total losses are larger in Southern California because of its much larger population. However, average losses per acre-foot of shortage are actually smaller in Southern California than in the San Francisco Bay Area as can be seen by comparing the third rows of each panel in Table 7, where each row presents welfare losses in terms of average loss per acre-foot of shortage. Marginal losses due to additional supply disruptions increase at an increasing rate so that the average loss per acre-foot of shortage is increasing in the size of the supply disruption. The 95% confidence intervals for each estimate

[9] See Appendix A for an illustrative example.

are presented in the second and fourth rows of each panel; these confidence intervals reflect the estimated variability in the price elasticities of demand recovered from the regression analysis. Due to non-linearities of the price elasticity in the expression for aggregate welfare losses, the confidence intervals for welfare losses are bootstrapped by cluster (water utility) in favor of confidence intervals based on analytic standard errors.

The subsequent rows of each panel in Table 7 provide some context for the welfare loss estimates. The fifth row presents the average household's willingness-to-pay (WTP) to avoid supply disruptions. For example, the WTP range of $64 to $633 per household to avoid a year-long shortage of 10% to 30% is not inconsistent with our expectations and appears plausible. The final row of each panel presents the household WTP measure in terms of percentage increase in expenditures on the volumetric rate component of the household's water bill, which lie between 13.2% and 130.2%. These percentage figures summarize the percentage increases in existing volumetric rates that consumers would be willing to pay to avoid disruptions.

Our loss calculation is based on the typical water use level of residential households in each utility's service area, and implicitly assumes that a water supply disruption of a given magnitude is met with proportional rationing on each tier of the pricing structure. Again, for utilities that meet a supply reduction by raising water rates predominantly on the higher tiers of the pricing structure, the actual welfare losses would be larger than the losses described above.

There are two final points we would like to make regarding Table 7. First, we assume the marginal cost of service delivery is $193 per acre-foot, which reflects that the marginal cost of service deliver is considerably less than the median tier price that typical residential consumers face–$1,232 per acre-foot. To see how the marginal cost affects the value of avoid a water supply disruption, we can bound the marginal costs of service delivery between $0 per acre-foot and $1,232 per acre-foot. These bounds correspond to the cases where the marginal cost of service delivery is zero (free) and where they are equal to the median tier price residential consumers pay (i.e. marginal cost pricing). Consistent with equation (3), the value of avoiding a supply disruption on a per acre-foot basis is the willingness-to-pay to avoid the supply disruption minus the marginal cost of service delivery. Thus, assuming \$0/AF for marginal cost generates a upper bound on the willingness-to-pay for a given supply disruption. Similarly, assuming the marginal cost of service delivery is equal to the median tier price faced by residential consumers generates a lower bound. To put these bounds into context, consider from Table 7 the estimate for the value of avoiding a 10% supply disruption in Southern California is \$1,440 per acre-foot. A lower bound for this estimate is \$402 per acre-foot and an upper bound is \$1,633 per acre-foot. The estimate for the value of avoiding a 30% supply disruption in Southern California is \$3,248 per acre-foot with a lower bound of \$2,210 per acre-foot and an upper bound of \$3,441 per acre-foot. This discussion highlights once again the fact that under average cost pricing which is often employed by public water utilities, the willingness-to-pay to avoid a supply disruption is considerably greater than the usual consumer surplus triangle.

Second, heterogeneity in price elasticities and price have a huge impact on losses across utilities. Figure (2) plots smoothed distributions of the value of avoiding supply disruptions on per acre-foot basis for different percent supply disruptions across the 53 urban water utilities considered in the welfare analysis. These results are consistent with the standard deviations reported in Table 6 and depicts the fact that heterogeneity in the value of avoiding supply disruptions becomes greater with larger disruptions. The value of avoiding supply disruptions on a per acre-foot basis mainly lies between a few hundred dollars and \$5,000 under a 10% disruption for most utilities; and between a few hundred dollars and \$12,500 under a 30% disruption. From a regional perspective, under a 30% disruption the losses per acre foot in the San Francisco Bay Area are over 60% larger than the average losses in Southern California, which is largely attributed to the differences in price elasticities and initial prices. This is not inconsequential as such a difference in value could influence the economic viability of large infrastructure projects designed to secure water supply reliability.

4.6 Allocative Efficiency

As a final exercise, we implement an efficient rationing regime to consider the allocative inefficiency of uniform percentage cut-backs (proportional rationing) across water utilities facing regional water supply disruptions in the presence of utility-level heterogeneity in price elasticities and initial prices when volumetric rates include a portion of the fixed costs. Based on the variation of average welfare losses reported in the square brackets of Table 6, we know that addressing allocative inefficiency will have distributional effects; however, as we will see the aggregate effect of the inefficiency is, perhaps surprisingly, small.

Table 8 reports the efficiency gains in the San Francisco Bay Area and Southern California in terms of absolute and percentage improvements of moving from a proportional rationing regime to an efficient rationing regime when facing shortages of 10%, 20%, and 30%. A 10% regional disruption in the San Francisco Bay Area results in \$29.4 million and \$26.1 million in welfare losses under proportional rationing and efficient rationing, respectively. Thus, the absolute improvement in welfare of moving from proportional to efficient rationing is approximately \$3.4 million. As expected, the welfare losses in levels under both forms of rationing are increasing in the size of the regional supply disruption. A 30% regional disruption in the San Francisco Bay area results in \$293.3 million and \$246.8 million in welfare losses under proportional rationing and efficient rationing, respectively. Thus, the absolute improvement in welfare is approximately \$46.5 million. Qualitatively, we see a similar pattern for Southern California–efficiency gains in absolute terms are increasing with the size of the regional supply disruption.

Interestingly, the pattern of efficiency gains in percentage terms of moving from a proportional rationing regime to an efficient rationing regime is divergent between the San Francisco Bay Area and Southern California. In the San Francisco Bay Area moving from a proportional rationing regime to an efficient rationing regime results in a 11.5% efficiency gain when faced with a 10% regional disruption and a 15.9% efficiency gain when faced with a 30% regional disruption. It appears efficiency gains are increasing in the size of the supply disruption. However, in Southern California moving from a proportional rationing regime to an efficient rationing regime results in a 13.3% efficiency gain when faced with a 10% regional disruption and a only a 6.1% efficiency gain when faced with a 30% regional disruption. We observe the surprising result that efficiency gains in percentage terms can actually *decrease* in the size of the regional disruption.

To unpackage this surprising result, we point out that the efficiency gains of moving from a proportional rationing regime to an efficient rationing regime during a shortage reflects the benefits of both moving to an efficient allocation under no shortage (which depends on heterogeneity across utilities in initial prices) and rationing demand from the efficient base allocation to an efficient allocation under shortage (which depends on heterogeneity across utilities in price elastiticies). In the San Francisco Bay Area, elasticities cluster around -0.15 and small deviations from -0.15 can generate large variations in marginal values under a 30% shortage, which leads to significant inefficiencies under proportional rationing. In Southern California, elasticities cluster around -0.19 and even somewhat large deviations from -0.19 do not generate sufficient variation in marginal values, even under a 30% shortage, to generate large efficiency gains in percentage terms.

We demonstrate the role of heterogeneity of price elasticies in determining efficiency gains with a thought exercise that reverses the patterns of percentage improvements reported for the San Francisco Bay Area in Table 8. We modify the shape of the demands curves for utilities in the San Francisco Bay Area so that the price elasticities cluster around -0.19 instead of -0.15. The efficiency gains in percentage terms when assuming these more elastic demands are 12.3% under a 10% shortage but only 9.2% for a 30% shortage. This is the same qualitative result of decreasing efficiency gains in percentage terms that we see for Southern California in Table 8. The result makes clear the importance of modeling utility-level heterogeneity in order to capture the distributive effects of water shortages.

5 Conclusions

In the economics of water utilities a simple, yet often overlooked fact, is that utilities load a large share of the high infrastructure costs onto the volumetric price of water they charge their customers. Therefore, the consumer surplus triangle which is often used to determine welfare losses due to a supply disruption is theoretically incorrect. Said differently, fixed costs are sunk at the time of a water supply disruption and so have no bearing on welfare outcomes. The welfare loss from a supply disruption, accordingly, can be many times greater than the loss evaluated using standard measures of compensating variation or equivalent variation in consumer utility functions.

A significant contribution this paper makes relates to the estimation of price elasticities using a panel data set comprised of 37 urban water utilities in California over the period 1996-2009. Our approach uses a utility fixed effects model as opposed to a pooled cross-sectional model, which allows us to take into account time-invariant omitted variables. We address concerns related to alternative forms of simultaneity bias by selecting a price measure that is adminstratively set and is not explicitly a function of consumption. Further, we instrument our price measure to address attenuation bias due to measurement error, and also test for heterogeneity in price elasticities across utilities. Our work empirically demonstrates that the price elasticity of residential water demand displays statistically significant variation across utilities. Accounting for this variation is essential for assessing the distribution of welfare losses, and evaluating the benefits of reliability associated with water infrastructure investments. The empirical results are robust to alternative specifications; however, an area of future research is to incorporate data on residential water conservation policies and to model the price elasticities for specific household water uses facing restriction.

Understanding variation in price elasticities across utilities will also aid water managers when allocating scarce water resources across space. We present evidence that efficiency gains of moving from proportional to efficient rationing can be substantial, for example, there is an 15.9% efficiency gain the San Francisco Bay Area under a shortage of 30%. However, in other cases these efficiency gains are not as large; an interesting finding is that utility-level variation in baseline prices and elasticities explains the somewhat unexpected patterns of percentage efficiency gains across space. The key finding is that the distribution of welfare impacts exhibits substantial variation across regions, which highlights the need to consider decentralized impacts of water supply disruptions in the design of efficient rationing rules.

Germane to the discussion is the fact that there is regional variation in the marginal cost of service delivery; hence, better regional data on these marginal costs should be an object of interest for water managers and policy-makers alike. Further, marginal costs relate explicitly to the source of supply–if a region has multiple supply sources then water managers and policy-makers must consider the supply source facing unreliability when evaluating the benefits of investing in a reliable alternative supply. A better understanding of the marginal costs of service delivery across space and for different supply sources will enhance the accuracy of welfare measures presented in our analysis.

In summary, we consider heterogeneous water demand functions to measure the welfare losses of urban water supply disruptions when baseline water rates are not allocatively efficient and for which a significant portion of the volumetric rate reflects fixed costs. One of the main welfare results show that when the volumetric rates also carry a portion of the fixed costs, then average welfare losses per acre-foot of shortage increase significantly; for example, under a 30% shortage accounting for this pricing structure increases the estimated welfare loss per acre-foot by over 40% to approximately $3,500. Another important finding is the large variation in welfare losses across water utilities, with losses from a 30% shortage varying from under $1,000 per acre-foot of shortage to over $12,000 per acre-foot. Finally, we point out that our welfare loss estimates are likely under-estimates if utilities employ water use specific restrictions such as no landscape irrigation to achieve cut-backs resulting from supply disruptions.

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Figure 1: Welfare Losses of Rationing under Tiered Pricing

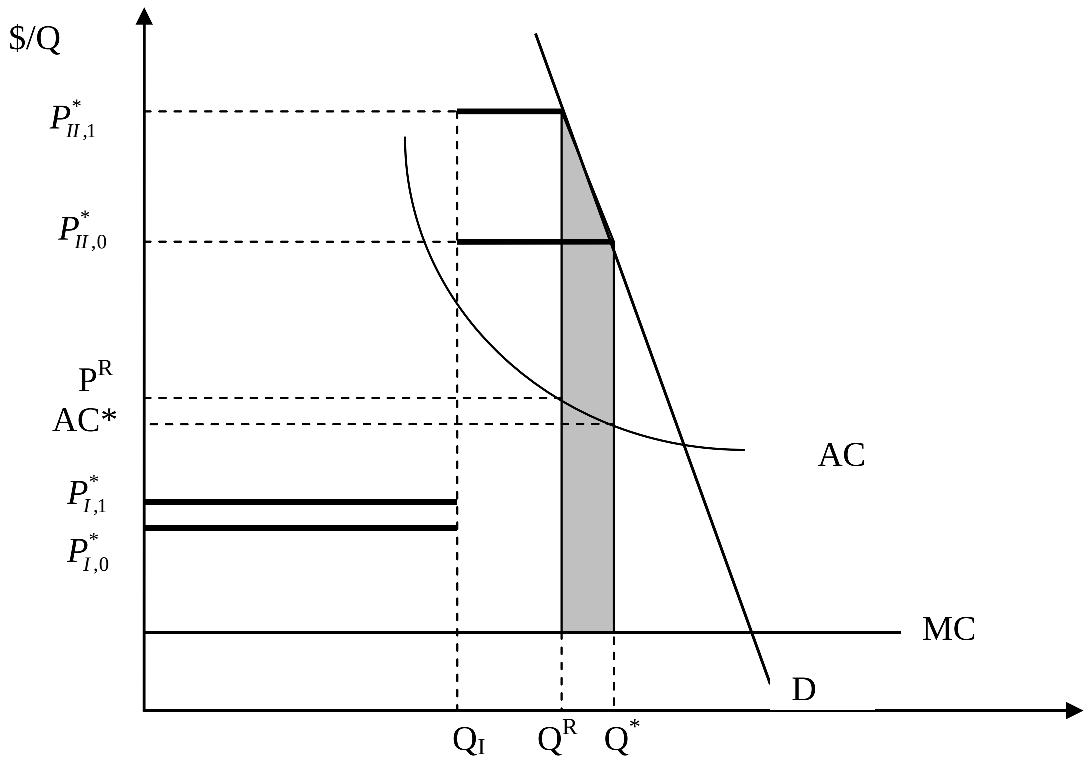

Figure 2: Heterogeneity across water utilities in ratepayer welfare losses conditioned on different percent supply disruptions

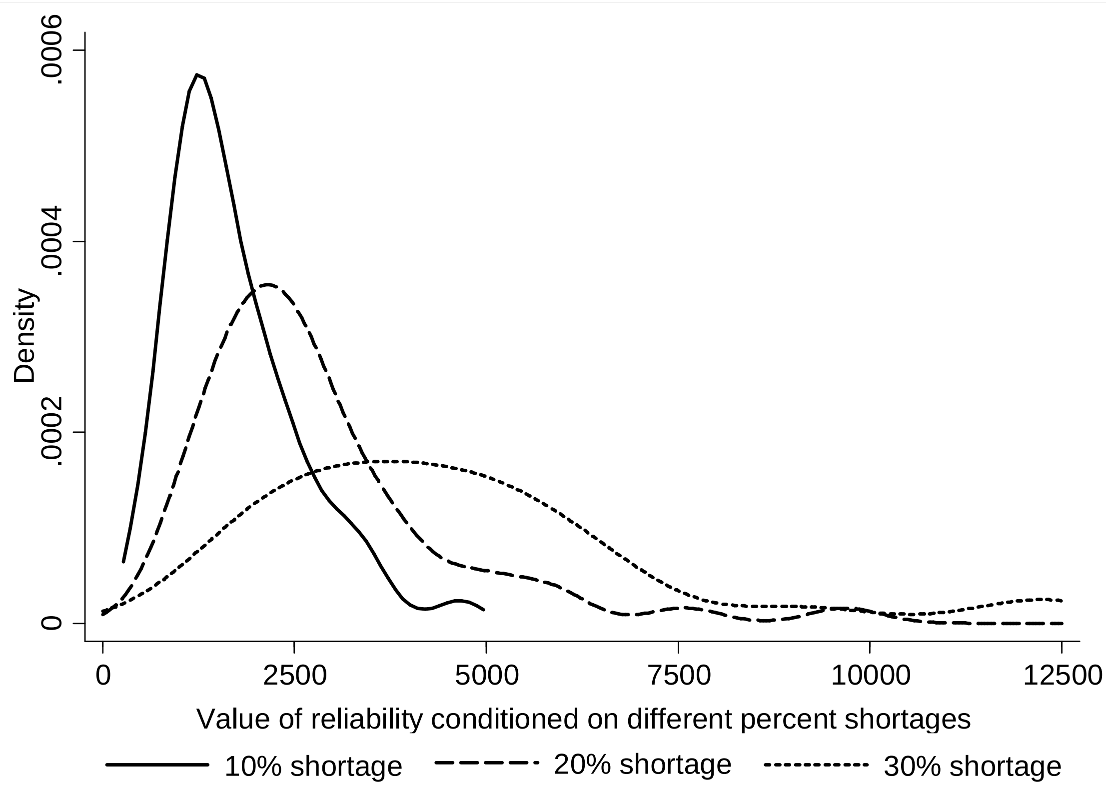

Table 1: Summary of average monthly household consumption and price per centum cubic feet (ccf) data used in the regression analysis

	(1)	(2)	(3)	(4)	(5)
Utility	Obs.	ccf /month	(S.D. of ccf /month)	Price /ccf	(S.D. of Price /ccf)
Alameda C.W.D.	13	12.78	(0.66)	1.83	(0.38)
Anaheim	11	19.21	(1.11)	1.26	(0.22)
Brisbane	9	5.66	(0.44)	2.98	(0.86)
Burbank	14	25.15	(2.29)	1.45	(0.30)
Burlingame	13	11.70	(0.60)	1.35	(0.60)
C.W.S. - Bear Gulch	13	26.11	(1.82)	2.24	(0.40)
C.W.S. - Mid Peninsula	13	12.22	(0.57)	2.10	(0.37)
C.W.S. - South San Francisco	13	9.36	(0.41)	1.72	(0.36)
City San Diego	7	12.77	(1.10)	2.32	(0.52)
Coastside	14	9.30	(0.82)	3.09	(0.92)
Daly City	13	8.76	(0.49)	2.91	(0.71)
East Palo Alto	13	14.30	(1.94)	1.77	(0.28)
Estero M.I.D.	14	12.55	(0.64)	1.31	(0.27)
Fullerton	14	20.25	(1.31)	1.30	(0.32)
Glendale	9	20.03	(1.39)	2.03	(0.23)
Hayward	14	10.45	(0.66)	1.93	(0.36)
Hillsborough	8	31.18	(2.01)	4.32	(0.86)
Long Beach	7	13.93	(0.67)	1.59	(0.06)
Los Angeles	11	17.88	(1.00)	3.04	(0.87)
Menlo Park	13	15.33	(1.09)	1.51	(0.19)
Mid-Peninsula	12	10.50	(0.59)	2.81	(1.20)
Millbrae	14	9.65	(1.10)	2.48	(0.90)
Milpitas	13	12.22	(0.83)	1.74	(0.49)
Mountain View	13	10.60	(0.69)	2.42	(0.48)
North Coast	13	8.95	(0.98)	3.97	(1.27)
Palo Alto	14	14.77	(0.97)	3.15	(1.08)
Pasadena	11	22.46	(1.10)	2.01	(0.57)
Purissima Hills	10	36.66	(2.69)	3.01	(1.47)
Redwood City	14	11.35	(1.01)	2.41	(0.57)
San Bruno	13	11.36	(0.84)	3.14	(0.92)
San Jose	14	9.23	(0.60)	1.56	(0.23)
Santa Ana	12	18.03	(1.99)	1.76	(0.55)
Santa Clara	14	13.90	(0.82)	1.60	(0.48)
Santa Monica	10	16.86	(1.01)	2.24	(0.55)
Skyline	12	11.95	(0.66)	8.16	(3.44)
Sunnyvale	14	13.11	(0.71)	1.90	(0.60)
Westborough	14	7.68	(0.86)	2.03	(0.44)
Unweighted Average	*12.24*	*14.82*	*1.04*	*2.39*	*0.66*

Table 2: Counts of utilities for the Year 2006 by number of tiers on Increasing Block Price (IBP) schedule

	(1)	(2)	(3)
No. of tiers	No. of utilities	Percentage share	Cummulative percentage share
1	11	29.73	29.73
2	8	21.62	51.43
3	8	21.62	72.97
4	4	10.81	83.78
5	2	5.41	89.19
6	4	10.81	100.00

Table 3: Residential annual water demand estimation

	(1)	(2)	(3)	(4)	(5)
	OLS	OLS	IV	OLS	IV
ln(Price)	0.173	-0.100***	-0.143***	-0.591***	-0.637***
	(0.120)	(0.033)	(0.046)	(0.194)	(0.242)
ln(Price)·ln(Income)				0.110**	0.113**
				(0.041)	(0.050)
Observations	453	453	453	453	453
Weather controls	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Utility fixed effects	No	Yes	Yes	Yes	Yes

Note: Standard errors clustered at the water utility level reported in parentheses: *** p<0.01, ** p<0.05, and * p<0.1.

Table 4: Robustness checks for residential annual water demand estimation

	(1)	(2)	(3)
	IV	IV	IV
ln(Price)	-0.137**	-0.126**	-0.132***
	(0.054)	(0.049)	(0.042)
ln(Price)·IBP	0.002		
	(0.045)		
ln(Price)·Drought			-0.014
			(0.018)
Observations	453	453	453
Weather controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Utility fixed effects	Yes	Yes	Yes
County specific t, t^2	No	Yes	No

Note: Standard errors clustered at the water utility level reported in parentheses: *** p<0.01, ** p<0.05, and * p<0.1.

Table 5: Estimated price elasticities and prices per acre-foot by utility

San Francisco Bay Area	ϵ	Price	Southern California	ϵ	Price
Alameda C.W.D.	-0.147	$1,102	Anaheim	-0.195	$775
Brisbane	-0.168	$1,941	Beverly Hills	-0.149	$1,679
Burlingame	-0.154	$1,028	Burbank	-0.197	$937
C.W.S. - Bear Gulch	-0.100	$1,398	Calleguas M.W.D.	-0.161	$1,129
C.W.S. - Mid Peninsula	-0.152	$1,319	Central Basin M.W.D.	-0.213	$995
C.W.S. - So. S.F.	-0.177	$1,089	Compton	-0.243	$834
Coastside	-0.125	$2,169	Eastern M.W.D.	-0.215	$1,532
Daly City	-0.169	$1,716	Foothill M.W.D.	-0.151	$1,423
East Palo Alto	-0.197	$1,050	Fullerton	-0.187	$1,405
Estero M.I.D.	-0.123	$754	Glendale	-0.205	$1,325
Hayward	-0.187	$1,102	I.E.U.A.	-0.189	$703
Hillsborough	-0.100	$2,169	Las Virgenes M.W.D.	-0.123	$895
Menlo Park	-0.131	$734	Long Beach	-0.216	$1,024
Mid Peninsula	-0.136	$1,967	Los Angeles	-0.213	$1,955
Millbrae	-0.158	$1,721	M.W.D. Orange County	-0.162	$996
Milpitas	-0.136	$1,095	Pasadena	-0.194	$1,527
Mountain View	-0.156	$1,415	San Diego C.W.A.	-0.193	$1,645
North Coast	-0.156	$2,448	San Fernando	-0.223	$614
Palo Alto	-0.123	$2,084	San Marino	-0.100	$767
Purissima Hills	-0.100	$2,755	Santa Ana	-0.209	$908
Redwood City	-0.153	$1,605	Santa Monica	-0.184	$2,156
SFPUC	-0.182	$706	Three Valleys M.W.D.	-0.178	$962
San Bruno	-0.168	$3,000	Torrance	-0.182	$1,116
San Jose Municipal	-0.129	$926	U.S.G.V. M.W.D.	-0.200	$615
Santa Clara	-0.144	$1,089	West Basin M.W.D.	-0.182	$1,170
Sunnyvale	-0.148	$1,335	Western M.W.D.	-0.194	$615
Westborough	-0.147	$1,280			

Table 6: Comparison of mean welfare losses per acre-foot by scenario & percent disruption

	Percent supply disruption		
Assumptions by scenario	10%	20%	30%
Base scenario (P=MC):			
- Common price elasticity	\$425	\$1,113	\$2,319
- Common prices	[\$0]	[\$0]	[\$0]
- No fixed-costs in volumetric price			
Scenario 1 (P=MC):			
- Heterogeneous price elasticities	\$438	\$1,169	\$2,508
- Common prices	[\$165]	[\$637]	[\$2,143]
- No fixed-costs in volumetric price			
Scenario 2 (P=MC):			
- Heterogeneous price elasticities	\$418	\$1,114	\$2,387
- Heterogeneous prices	[\$357]	[\$1,222]	[\$3,731]
- No fixed-costs in volumetric price			
Scenario 3 (P>MC):			
- Heterogeneous price elasticities	\$1,458	\$2,153	\$3,426
- Heterogeneous prices	[\$834]	[\$1,649]	[\$4,102]
- Portion of fixed-costs in volumetric price			

Note: Standard deviation for mean welfare losses per acre-foot across 53 urban water utilities is reported in square brackets. We emphasize that the figures reported in the square brackets are not standard errors; instead, they are the standard deviations associated with the calculation of mean welfare loss per acre-foot for the 53 urban water utilities under differents sets of supply disruptions and assumptions. Notice in the base scenario we assume away heterogeneity in mean welfare losses across water utilities. In Scenario 1 we observe the overall mean welfare losses are comparable to the base scenario; however, accounting for heterogenous price responses introduces heterogeneity in utility-level mean welfare losses across water utilities. In Scenario 2 the overall mean welfare losses do not change much, but the standard deviation in utility-level mean welfare losses across water utilities approximately doubles. Accounting for heterogeneous prices responses and initial rates is clearly important for capturing the distributional effects of supply disruptions. In Scenario 3 we account for the fact that volumetric rates carry a portion of the fixed-costs; the losses triple relative to Scenario 2 for a 10% shortage and go up over 40% for a 30% shortage.

Table 7: Welfare losses due to shortages of 10%, 20% and 30% in the Single Family Residential (SFR) demand sector

Panel A: San Francisco Bay Area Utilities			
Quantity-weighted average price : $1,248/AF; Household-weighted avg. elasticity: -0.158			
Total SFR demand (AF): 177,269; Total SFR households: 454,799			
Percent disruption	10%	20%	30%
Total loss ($ millions)	$29	$100	$288
[95% Bootstrapped C.I.]	[$25 - $35]	[$70 - $152]	[$157 - $574]
Average loss ($/AF)	$1,653	$2,815	$5,414
[95% Bootstrapped C.I.]	[$1,404 - $1,999]	[$1,976 - $4,278]	[$2,944 - $10,795]
Household WTP($/year)	$64	$219	$633
% increase in expenditures	13.2%	45.1%	130.2%

Panel B: Southern California Utilities			
Quantity-weighted average price : $1,231/AF; Household-weighted avg. elasticity: -0.193			
Total SFR demand (AF): 177,269; Total SFR households: 3,534,990			
Percent disruption	10%	20%	30%
Total ($ millions)	$285	$828	$1,930
[95% Bootstrapped C.I.]	[$251 - $390]	[$628 - $1,668]	[$1,215 - $6,318]
Average ($/AF)	$1,440	$2,094	$3,248
[95% Bootstrapped C.I.]	[$1,268 - $1,970]	[$1,587 - $4,219]	[$2,047 - $10,648]
Household WTP($/year)	$81	$234	$545
% increase in expenditures	11.7%	34.0%	79.2%

Note: Square brackets report 95 percent confidence intervals for our estimates of total welfare losses and average welfare losses per acre-foot (AF) of supply disruption. Due to the fact that the elasticity estimates enter non-linearly into the welfare expression, these are bootstrapped confidence intervals with bootstrapping occuring at the water utility level. The Household WTP measure divides the Total loss reported in the first row by the total number of single family residential households in the region. The % increase in expenditures uses the welfare loss estimates to calculate how much households would be willing to increase their existing expenditures in percentage terms in order to avoid the percent disruption identified at the top of the corresponding column.

Table 8: Summary of Efficiency Gains Generated by Moving from Proportional Rationing to Efficient Rationing Regimes Under Shortages of 10%, 20% and 30%

Regional percent disruption	10%	20%	30%
Efficiency gains in the San Francisco Bay Area:			
Absolute improvements (millions)	\$3.4	\$11.4	\$46.5
Percentage improvements	11.5%	11.3%	15.9%
Efficiency gains in Southern California:			
Absolute improvements (millions)	\$38.0	\$60.2	\$116.7
Percentage improvements	13.3%	7.3%	6.1%

Appendix A: Welfare losses with an arbitrary number of pricing tiers

Consider the welfare implications of a water shortage in the case of identical own-price elasticity of demand for all households and proportional rationing of all pricing tiers. This setting accords with circumstances in which individual water utilities raise the price of each tier symmetrically by a constant percentage. Actual welfare losses would be larger in cases where water rates rise by larger percentages in higher tiers than in lower tiers.

Let n denote the number of households in a water utility's service area. Let P_j^* denote the equilibrium price paid for the last unit of water consumed by household j, where $j = 1, 2, 3, \ldots, n$. Now consider the aggregate welfare loss among households in the case of constant elasticity of demand for each household,

$$P_j = AQ_j^{\frac{1}{\varepsilon}} \tag{14}$$

where $\varepsilon < 0$ is the elasticity of household water demand and A_j is a parameter that scales the magnitude of household demand to a lower or higher pricing tier.

Suppose further that the water utility sets rates to proportionally ration water consumption across all households. In this case, the quantity of water consumed after rationing by household j, $Q_{j,1}^*$, relates to the initially consumed quantity of water, $Q_{j,0}^*$, according to:

$$Q_{j,1}^* = (1 - r)Q_{j,0}^* \tag{15}$$

where r is the percentage of water rationed at each household. Following equation from the manuscript we arrive at the following expression for welfare losses following a supply disruption r:

$$L_j(r) = \frac{\varepsilon}{1+\varepsilon} P_j^* Q_j^* [1 - (1-r)^{\frac{1+\varepsilon}{\varepsilon}}] - \int_{Q_j(r)}^{Q_j^*} c(x)dx. \tag{16}$$

Aggregating losses across the n households yields:

$$L(r) = \frac{\varepsilon}{1+\varepsilon}\bar{P}_0\bar{Q}_0[1-(1-r)^{\frac{1+\varepsilon}{\varepsilon}}] - \int_{\bar{Q}_0}^{\bar{Q}_1} c(x)dx \tag{17}$$

where $\bar{Q}_0 = \sum Q^*_{j,0}$ and $\bar{Q}_1 = \sum Q^*_{j,1}$ are the aggregate quantities of water purchased in the region in the initial period and shortage period; $\bar{P}_0$ is a price index that represents the weighted average of equilibrium prices across households making marginal water purchases on an arbitrary number of pricing tiers and is given by:

$$\bar{P}_0 = \frac{\sum P^*_j Q^*_{j,0}}{\sum Q^*_{j,0}}. \tag{18}$$

The calculation of the actual welfare losses of supply disruption in equation (17) is complicated by two factors. First, the degree of water rationing across households need not be uniform and most water utilities raise prices disproportionately on the upper pricing tiers to target the largest water consumers. In the case of the shortage rates used by LADWP as discussed in the main text, the levels of water rationing at a price elasticity value of -0.16 estimated by Renwick and Green (2000), would imply a 2.4% quantity reduction for households with an equilibrium level of purchases on the lowest pricing tier and a 9% quantity reduction for households with an equilibrium level of purchases on the highest pricing tier.

Second, price indices of the form in equation (18) are not publicly reported by water utilities. Nevertheless, it is useful to compare the welfare implications from this price index to the implications derived from using the average price received for water by a utility. Given a share of households that purchase an equilibrium quantity of water on higher tiers of the pricing structure, the average price received for water by utilities is distorted downwards from the price index in (18) by the volume of water that high demand users acquire at lower rates. For example, in the case of three pricing tiers (identified as I, II, III), the average price of water received by a utility serving one consumer of each demand type (identified as consumers 1, 2, 3) is given by:

$$\bar{P}_R = \frac{P_I^*(Q_1^* + 2Q_I) + P_{II}^*(Q_2^* + Q_{II} - 2Q_I) + P_{III}^*(Q_3^* - Q_{II})}{Q_1^* + Q_2^* + Q_3^*} \tag{19}$$

which is clearly lower than $\bar{P}_0$. Formally,

$$\bar{P}_0 - \bar{P}_R = \frac{2Q_I(P_{II}^* - P_I^*) + Q_{II}(P_{III}^* - P_{II}^*)}{Q_1^* + Q_2^* + Q_3^*} > 0. \tag{20}$$

Because the welfare loss in (17) is monotonically increasing in price, use of the average price, $\bar{P}_R$, in place of the price index, $\bar{P}_0$, understates welfare losses.