Theoretically consistent welfare estimation under block pricing: the case of water demand

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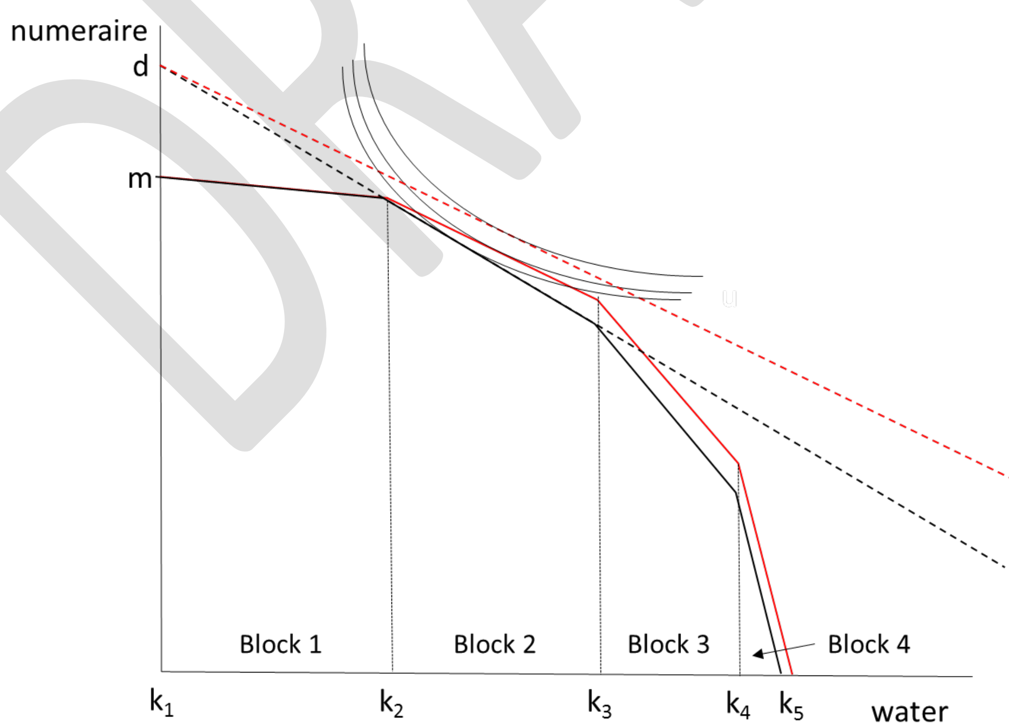
Motivation

The two-error discrete-continuous choice (DCC) model has become a popular approach for modeling consumer choice under block rate pricing. Originally developed by Burtless and Hausman (1978) for labor supply, the approach has been surveyed and reviewed by Moffitt (1986, 1990) and adapted by Hewitt and Hanemann (1995) and Pint (1999) for applications to water demand. Waldman (2000, 2005) and Hewitt (2000) generalized the associated likelihood function which Olmstead et al. (2007), Olmstead (2009), and Baerenklau et al. (2014a) used in recent investigations of increasing block rate water pricing.

The DCC model has been critiqued by Strong and Smith (2010) who argue that welfare analysis is problematic within a DCC framework because, as noted by Bockstael and McConnell (1983), the Marshallian demand function does not exist when the budget constraint is nonlinear. The problem can be seen in figure 1. Suppose that a consumer optimally selects consumption in block 2 when the budget set is given by the solid black line. If a Marshallian demand function $x(p,d)$ exists that describes optimal consumption conditional on selecting this block, then we should be able to derive it by holding virtual income d fixed and changing the block price p (from the dashed black line to the dashed red line which is parallel to the solid red line in block 2). But doing this will violate the budget constraint because the price change pivots around the point (k_1, d) whereas the budget facet pivots around the kink point at k_2. Thus consumption predicted by $x(p,d)$ can't be optimal, so $x(p,d)$ can't be the Marshallian demand.

Figure 1: Modeling consumption response to price changes under block rates.



The figure makes it clear that changing the price of an interior block without violating the budget constraint necessarily involves a simultaneous change in the virtual income associated with that block. This suggests that a solution to the problem of accurately predicting the consumption response to a price change under block rates is to simply adjust virtual income accordingly rather than hold it fixed. While this is true, it works only for small price changes (such as depicted in figure 1) that do not cause consumers to move from one facet of the budget set to a kink point or to another facet. For large price changes, this approach will yield incorrect results. As Bockstael and McConnell (1983) point out, accurately predicting the consumption response to large price changes requires a model that includes not only the local conditions faced by the consumer (i.e. block price and virtual income), but also the global properties of the budget constraint (i.e. prices in other blocks and locations of kink points).

The upshot of this is that, rather than expressing demand as an analytical function, demand must be expressed as an implicit solution to the set of Kuhn-Tucker conditions describing utility maximization subject to multiple linear constraints. This has important implications for welfare analysis. Foremost, it means that the indirect utility function cannot be derived by substituting analytical expressions for demand into the direct utility function. And because there is no analytical expression for indirect utility, there are no analytical expressions for Hicksian welfare measures.[1] Instead, as suggested by Strong and Smith (2010), the analyst must utilize an empirical framework that allows recovery of the parameters describing the direct utility function. Strong and Smith (2010) argue that this approach would provide a methodology that could handle non-marginal changes in price structures; but their subsequent analysis goes in a different direction due to lack of appropriate household level data. This article presents such a methodology and applies it to household level water demand under increasing block rate pricing to evaluate the welfare effects of a recent rate structure change. The methodology is general and can be applied to any instance of block rate pricing with appropriate data.

The two-error DCC model

The two-error DCC model was developed to deal with the problematic nature of nonlinear (specifically block rate) prices that can confound attempts to estimate how quantities respond to changes in such prices.[2] The specific problem in a standard single-error regression model with nonlinear prices is that the observed price is endogenous because it depends on the observed consumption level which depends on the error term. Thus, in such a model, the error term, observed consumption level, and observed price are all correlated. This tends to bias the coefficients derived from a regression of quantity on price.

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[1] Nor are there analytical expressions for changes in consumer surplus due to large price changes, again due to the lack of an analytical expression for demand.

[2] The purpose of this section is not to provide a complete overview of the DCC model, but rather to present the salient features for this analysis. For a more thorough overview, refer to Burtless and Hausman (1978) and Hewitt and Hanemann (1995).

The DCC model breaks the correlation between the price and error terms by breaking up the consumption decision into two sequential steps. The first step is the selection of the optimal consumption block and the second step is the selection of the optimal consumption level within that block.[3] The benefit of this approach is that conditioning the second choice on the first allows the price to enter the analysis as a constant. To see this, reconsider figure 1 and again suppose that a consumer's optimal consumption is in the interior of block 2. Whether the consumer faces the block rate price structure with income m, or a constant block 2 price with virtual income d, the optimal decision is the same. Therefore the relevant marginal price—the one driving the observed consumption level—is the block 2 price, which can be treated as a constant conditional on the choice to consume in this block.

The challenge associated with implementing this approach is that typically the optimal consumption level (and perhaps also the optimal block) is not observed by the analyst. Rather, the observed consumption (and block) provides a signal about the optimal consumption (and block), but the signal is noisy. Therefore the relevant marginal price—the one that drove the observed outcome—is unobserved. To deal with this, the DCC framework effectively posits a probability distribution over the marginal prices (actually over the solutions to the block-specific optimization problems) and incorporates this distribution into the likelihood function used to estimate the model parameters. The rationale for using such a distribution is that households have heterogeneous preferences, and although each household knows its own preferences, the analyst does not know any with certainty. Thus a household knows its marginal price and which of several block-specific optimization problems it is solving while the analyst knows only the distribution of preferences in the population and thus must work with expectations.

This preference heterogeneity is the first of two errors in the two-error DCC model. The second error is an IID consumption shock that subsequently perturbs the optimal consumption and produces the observed consumption.[4] Preference heterogeneity is observed by a household before making its optimal choice; thus it affects that choice. The consumption shock occurs after the optimal choice has been made; thus it does not affect the optimal choice. The upshot is that the heterogeneous preferences term is correlated with price, but this is not problematic because the term enters as a regressor in the estimation. Furthermore, the consumption shock, which is treated as an econometric error, is uncorrelated with price because prices are fixed in each block-specific optimization problem.

To implement this approach, it is typically assumed that a single function $x(p, d)$ exists that approximates household demand in any block by plugging in the block-specific values of p and d (Hewitt and Hanemann 1995). Preference heterogeneity ε is assumed to enter additively,

[3] The framework also accommodates optimal consumption between blocks at a kink point. For purposes of exposition, and without loss of generality, I disregard these corner solutions for now.

[4] For this reason, optimal consumption is often referred to as planned consumption in this context.

such that a household's optimal choice is given by $x(p, d) + \varepsilon$. The consumption shock η also is assumed to enter additively, such that the observed choice is given by $x(p, d) + \varepsilon + \eta$.

As in figure 1, denote the blocks by $j \in \{1, \dots, J\}$ and the block boundaries (kink points) by k_j, $j \in \{1, \dots, J + 1\}$. By construction, a household chooses to consume in block j when its optimal choice $x(p_j, d_j) + \varepsilon$ is greater than k_j and less than k_{j+1}, or: $k_j - x(p_j, d_j) < \varepsilon \leq k_{j+1} - x(p_j, d_j)$. Similarly, a household chooses to consume at kink point j when its optimal choice $x(p_{j-1}, d_{j-1}) + \varepsilon$ is greater than k_j and its optimal choice $x(p_j, d_j) + \varepsilon$ is less than k_j, or: $k_j - x(p_{j-1}, d_{j-1}) < \varepsilon \leq k_j - x(p_j, d_j)$. Given these optimal choices of block and kink points, and assuming infinite support for ε, observed consumption can be expressed as (Hewitt 2000):

$$x = \begin{cases} k_1 + \eta, & -\infty < \varepsilon \leq k_1 - x(p_1, d_1) \\ x(p_1, d_1) + \varepsilon + \eta, & k_1 - x(p_1, d_1) < \varepsilon \leq k_2 - x(p_1, d_1) \\ k_2 + \eta, & k_2 - x(p_1, d_1) < \varepsilon \leq k_2 - x(p_2, d_2) \\ x(p_2, d_2) + \varepsilon + \eta, & k_2 - x(p_2, d_2) < \varepsilon \leq k_3 - x(p_2, d_2) \\ k_3 + \eta, & k_3 - x(p_2, d_2) < \varepsilon \leq k_3 - x(p_3, d_3) \\ \vdots & \vdots \\ x(p_J, d_J) + \varepsilon + \eta, & k_J - x(p_J, d_J) < \varepsilon \leq k_{J+1} - x(p_J, d_J) \\ k_{J+1} + \eta, & k_{J+1} - x(p_J, d_J) < \varepsilon < \infty \end{cases} \tag{1}$$

The probability of observing a consumption level is given by (Olmstead 2009):

$$Pr(x) = \begin{cases} Pr\begin{pmatrix} \eta = x - k_1, \\ -\infty < \varepsilon \leq k_1 - x(p_1, d_1) \end{pmatrix} + \\ Pr\begin{pmatrix} \varepsilon + \eta = x - x(p_1, d_1), \\ k_1 - x(p_1, d_1) < \varepsilon \leq k_2 - x(p_1, d_1) \end{pmatrix} + \\ Pr\begin{pmatrix} \eta = x - k_2, \\ k_2 - x(p_1, d_1) < \varepsilon \leq k_2 - x(p_2, d_2) \end{pmatrix} + \\ Pr\begin{pmatrix} \varepsilon + \eta = x - x(p_2, d_2), \\ k_2 - x(p_2, d_2) < \varepsilon \leq k_3 - x(p_2, d_2) \end{pmatrix} + \\ Pr\begin{pmatrix} \eta = x - k_3, \\ k_3 - x(p_2, d_2) < \varepsilon \leq k_3 - x(p_3, d_3) \end{pmatrix} + \\ \vdots \\ Pr\begin{pmatrix} \varepsilon + \eta = x - x(p_J, d_J), \\ k_J - x(p_J, d_J) < \varepsilon \leq k_{J+1} - x(p_J, d_J) \end{pmatrix} + \\ Pr\begin{pmatrix} \eta = x - k_{J+1}, \\ k_{J+1} - x(p_J, d_J) < \varepsilon < \infty \end{pmatrix} \end{cases} \tag{2}$$

A simplified expression for the sample likelihood function under normality can be found in Waldman (2000, 2005) and Hewitt (2000).

As can be seen in (1), and consistent with the preceding discussion, the preference heterogeneity term determines the optimal discrete choice for any household and effectively breaks the correlation between the price variable and the econometric error. The consumption shock is appended to expressions that have constant prices and is thus uncorrelated with price.

Aside from the fact that $x(p, d)$ cannot be interpreted as a Marshallian demand function, one additional feature of this framework merits discussion. Specification of the intervals on the right-hand side of (1) is crucial to the analysis not only because it forms the basis for piece-wise integration over ε, but also because it determines whether the budget-constrained utility maximization problem has a unique solution. Proper integration over ε is required both for deriving maximum likelihood estimates and also for calculating expected demand given those estimates; a unique solution is required for theoretical consistency given the standard assumption of a strictly quasi-concave utility function. Achieving both requires that the union of the interval sets must be the entire support of ε and the intersection must be null (i.e. $x(p_j, d_j) > x(p_{j+1}, d_{j+1}),\ \forall j$). However, without imposing this condition—which embodies the Slutsky constraint—on the model directly, there is no guarantee that it will be satisfied. Whether analysts do this in practice is unclear (see Pint (1999) for more on this issue).

Welfare estimation in the DCC framework

Welfare estimation in the DCC framework is straightforward provided the underlying direct utility function is known. For empirical work, this precludes the commonly used log-linear demand system.[5] The linear demand system also is undesirable because additional effort is needed to address the non-negativity of demand (e.g. modeling as a tobit). An appealing framework is the semi-log demand system for which the direct utility function is known and which also satisfies non-negativity. Relevant components of the semi-log system for two goods are shown in table 1 (Bockstael et al. 1989).[6]

Here, x is the good of concern (water), d is (virtual) income, $c(x)$ is the cost of consuming x, and $\{\alpha, \beta, \gamma\}$ is a set of estimable parameters. Note that α can be the scalar product of vectors of parameters and regressors; and the second good in the system is assumed to be the numeraire and thus has been replaced by $\big(d - c(x)\big)$.

Reconciling this system with the DCC framework requires both a conceptual change and the addition of the two error terms. The conceptual change affects how $x^*(p, d)$ is interpreted in the DCC framework. Rather than as a Marshallian demand function, $x^*(p, d)$ should be

[5] The Cobb-Douglas utility function produces demand equations that are linear in the logs of income and price, but the associated coefficients must be 1 and -1, respectively.

[6] The direct utility function differs slightly from Bockstael et al. (1989) which contains a typo.

Table 1: Semi-log demand system

Direct utility	$u(x) = \frac{\beta+\gamma x}{-\gamma\beta} exp\left[\frac{\gamma\big(\alpha x - \beta\big(d - c(x)\big) - xlnx\big)}{\beta+\gamma x}\right]$
Marshallian demand	$x^*(p,d) = exp(\alpha + \beta p + \gamma d)$
Expenditure function	$e(p,u) = -\frac{1}{\gamma} ln\left[-\gamma u - \frac{\gamma}{\beta} exp(\alpha + \beta p)\right]$

interpreted simply as the tangency condition for optimal consumption conditional on the choice to consume in a particular block. Additional properties normally attached to this function (when appropriate to interpret as a Marshallian demand function) do not apply—as in Strong and Smith (2010), $x^*(p,d)$ is considered to be an estimating equation but nothing more.

To append the error terms, first take the log of x^* and redefine this expression using notation from the DCC framework: $x(p,d) \equiv ln\big(x^*(p,d)\big)$. Thus a household's observed consumption is given by $x(p,d) + \varepsilon + \eta$. Next, recall that ε represents preference heterogeneity and is thus a component of the utility function, whereas η is an *ex post* consumption shock that affects utility only through x. It is therefore convenient to redefine $\alpha \equiv \alpha + \eta$ when working with the direct utility function.

Maximum likelihood estimation using the DCC framework produces point estimates for $\{\alpha, \beta, \gamma, \sigma_\varepsilon, \sigma_\eta\}$, where σ_ε and σ_η are the standard deviations for the error terms. With these estimates in hand, it is straightforward to calculate expected utilities under block rate pricing by numerically integrating over the distributions for ε and η. With a designated reference price level, it is similarly straightforward to calculate the expected expenditures associated with these expected utilities, again by using numerical integration techniques. Holding this reference price level fixed also permits calculation of expected Hicksian welfare measures associated with changes in features of the block rate structure; or in comparison to entirely different price policies (e.g. uniform pricing) or non-price policies (e.g. quantity restrictions). These measures are derived by simply comparing the expected expenditures under different policies.

Application to allocation-based water rates

The standard approach for pricing goods and services in a market economy is uniform pricing: each unit is priced the same regardless of the amount consumed, the characteristics of the consumer, and the conditions under which consumption occurs. Block rate pricing refers to the case when the cost per unit varies with the amount consumed. An increasing (decreasing) block rate is when the first units are priced relatively low (high) and subsequent units are priced higher (lower), so that the price per unit rises (falls) with consumption in a stepwise manner.

Allocation-based water pricing is an innovative type of increasing block rate structure in which the block sizes vary according to household-specific characteristics (e.g., number of residents, irrigated area, unusual circumstances such as medical need), environmental conditions (e.g., evapotranspiration), and a judgment by the water utility regarding what constitutes efficient use given those characteristics and conditions. This means that price structures can differ across households at any time, and through time for any household. A household's efficient level of use is called its "water budget," and thus a household that consumes beyond its budget is deemed to be using water inefficiently. Prices tend to be relatively low for "in budget" water consumption, and much higher for "over budget" consumption.

Allocation-based rates are thought to have significant advantages over uniform and fixed block rate structures. Foremost, allocation-based rates are thought to provide a strong conservation incentive because the block sizes depend on household characteristics. Therefore all households face higher prices as consumption increases, whereas smaller households rarely enter the upper blocks under fixed block rate pricing. Baerenklau et al. (2014b) estimate that the Eastern Municipal Water District of Southern California (EMWD) reduced demand by 10-15% in the first 2-3 years following implementation of allocation-based rates while raising the average price paid for water by only 3% in real terms. The same study estimates that uniform rates would have had to rise by 30% in real terms to achieve the same reduction in demand. By comparison, Olmstead et al. (2005) find that much of the observed "rate structure effect" associated with the adoption of fixed block rates is actually an endogenous selection effect.

Allocation-based rates also address equity concerns by providing each household with a block of low-priced water to satisfy the most essential uses, such as drinking, cooking and cleaning, while charging higher prices for less essential uses such as landscaping. Because the highest prices are paid only by households that exceed their designated water budgets, allocation-based rates should be more politically acceptable than fixed block rates due to their perceived fairness. Baerenklau et al. (2014b) find empirical support for this argument: EMWD's rate structure reduced the consumption of the most inefficient tercile of households by 25-30%, compared to only 5% for the most efficient tercile. However, progressiveness in consumption efficiency does not necessarily imply progressiveness in terms of welfare effects. The purpose of the present study is to investigate the distribution of welfare effects of the EMWD rate change using the framework described in the preceding sections.

Data

The dataset for this study is the same as that used in Baerenklau et al. (2014a). The data are drawn from residential account records maintained by EMWD, a member agency of the Metropolitan Water District of southern California. EMWD serves a diverse region of western Riverside County that covers 542 square miles and has a population of over 768,000 (EMWD

2013). As of 2012, EMWD provided around 90,000 acre-feet of water to approximately 136,000 domestic water service accounts and a much smaller number of agricultural and irrigation water service accounts (EMWD 2013).

Prior to April 2009, EMWD charged each household a fixed daily service charge plus a uniform price per unit of water consumed. Beginning in April 2009, EMWD changed from uniform pricing to allocation-based rates to promote greater conservation. The rate structure has four blocks. The cumulative block sizes are calculated as follows:[7]

Block 1. Indoor water use: $w_1 = (HHS \times PPA) \times DF + IV$

Block 2. Outdoor water use: $w_2 = w_1 + (ET \times CF \times IA + OV) \times DF$

Block 3. Excessive water use: $w_3 = 1.5 \times w_2$

Block 4. Wasteful water use: water use in excess of w_3

Variables used to calculate block sizes are household size (HHS), per-person allowance (PPA), drought factor (DF), indoor variance (IV), evapotranspiration (ET), conservation factor (CF), irrigated area (IA), and outdoor variance (OV). HHS is reported to EMWD by each household;[8] PPA is set by EMWD at 60 gallons per day; DF is set less than or equal to 1 depending on environmental conditions;[9] IV is negotiated between EMWD and households that report unusual indoor circumstances such as medical need or in-home daycare; ET is derived from real-time measurements for a reference crop which are then adapted to 50 designated microclimate zones within the EMWD service area; CF converts the reference crop ET to turfgrass ET;[10] IA is reported to EMWD by each household;[11] and OV is negotiated between EMWD and households that report unusual outdoor circumstances such as maintenance of large animals or turfgrass establishment.

Block-specific prices are set such that $p_1 < p_2 < p_3 < p_4$, where p_k is the price charged for block *k*. A household's water budget is defined as the first two blocks, or cumulative consumption of w_2. Consumption above w_2 is deemed to be "excessive" or "wasteful" and is thus charged a significantly higher price than consumption below w_2. It is worth emphasizing that w_2 and w_3 are functions of ET and thus fluctuate from month-to-month. When ET is high, households are allocated larger monthly water budgets (i.e., more water in blocks 2 and 3); when ET is low, households are allocated smaller budgets.

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[7] The block labels (i.e., indoor, outdoor, excessive, and wasteful) are EMWD's terms.

[8] EMWD uses a default value of 3 if a household does not report the household size, and requires verification if a reported value exceeds 9 people.

[9] In this dataset, DF = 1 for all observations.

[10] Most water districts assume a baseline of turf grass given its high ET relative to most other grasses and plants; consequently, these districts are providing an overly-generous allocation for ET.

[11] EMWD uses Riverside County Assessor data to calculate a default value (up to a maximum of 6000 sq-ft) if a household does not report the irrigated area, and requires verification if reported values seem excessive.

The dataset includes 13,565 residential accounts with uninterrupted monthly water use records between January 2003 and September 2012. The fact that these accounts remained open is a good indication that there were no tenancy changes in these households during this period.[12] In addition to monthly water consumption data, EMWD also provided information on prices paid by each account, the household size (HHS) and irrigated area (IA) associated with each account, dates when households were asked to voluntarily increase their water conservation efforts, monthly ET under water budgets for each of the 50 microclimates, and the relevant microclimate for each account.[13] EMWD also provided the latitude and longitude of the meter for each account which enables georeferencing against census data to obtain information on income and education at the tract level.

Summary statistics for the full dataset are presented in Table 2.[14] Conservation requests refer to the fraction of months in which households were asked to increase water conservation efforts, typically due to system maintenance or heat waves. I do not include data on EMWD's other water conservation program efforts (e.g., rebates for high-efficiency toilets, washers, shower heads, and sprinkler nozzles) because the estimated savings from such programs amounts to less than 0.5% of residential deliveries. Nominal and real prices are the prices charged per hundred cubic feet (CCF) of water (one uniform rate from 2003-08; four increasing block rates from 2009-12). Under uniform-rate pricing, these prices are the same as the average prices paid by households. However under water budgets, the average price paid is a function of water consumed and thus is listed separately in the table. [15] As in Strong and Smith (2010), budgets are based on census income (Minnesota Population Center 2011) and are adjusted for the fraction of income typically spent on the category of "utilities, fuels, and public services." (U.S. Bureau of the Census 2012).[16] Budgets also are adjusted for temporal changes in per-capita personal income for the Ontario-Riverside-San Bernardino metropolitan statistical area (U.S. Bureau of Labor Statistics 2013). Education is expressed as the fraction of the census tract reporting "some college" or more education (U.S. Bureau of the Census 2012). Household size, irrigated area, and education are treated as constant characteristics because I lack information on monthly changes in these variables.[17]

[12] An exception could be rental properties for which the utility accounts are registered to the owner rather than the tenants. I am not able to identify such accounts in this dataset.

[13] Monthly ET under uniform pricing was estimated by Baerenklau et al. (2014a) using data from the California Irrigation Management Information System (CIMIS).

[14] Data for 2012 is from January through September only and is thus omitted from the table for purposes of comparison. Data for 2012 is included in the regression analyses.

[15] Average price paid in 2009 is a blend of uniform rates for January through March (nominally unchanged from 2008) and block rates for April through December (shown in the table).

[16] Using data from the 2010 Consumer Expenditure Survey, Baerenklau et al. (2014a) estimate the following relationship between budget (y) and income (m) for the sample: $y = 99.8941m^{0.3339}$, R^2 = 0.9915.

[17] Census data suggests that overall education levels in the study area remained fairly constant from 2000-2010.

Table 2: Summary statistics.

Variable	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Consumption (CCF/month)[a]	20.70	21.14	20.12	20.77	20.99	19.74	17.77	15.99	15.73
ET (in/month)[b]	4.67	4.87	4.59	4.73	4.87	4.81	4.70	4.55	4.85
Conservation requests	0.17	0.00	0.08	0.25	0.08	0.08	0.08	0.00	0.08
Nominal price ($/CCF)	1.43	1.46	1.53	1.62	1.69	1.85	1.27 2.33 4.17 7.63	1.43 2.61 4.68 8.56	1.44 2.64 4.73 8.65
Nominal average price paid ($/CCF)							1.93	2.10	2.05
Real price (2010$/CCF)	1.66	1.66	1.68	1.72	1.77	1.86	1.30 2.37 4.25 7.78	1.43 2.61 4.68 8.56	1.39 2.54 4.55 8.33
Real average price paid (2010$/CCF)							1.98	2.10	1.98
Real budget (2010$/month)	316.26	317.45	318.05	319.20	320.78	316.70	311.07	309.96	309.44
Household size (#)	3.53								
Irrigated area (sq-ft)	4,177								
Education[c]	0.50								

[a] CCF = hundred cubic feet.

[b] A principle components analysis on all available weather data during the observation period for one of the CIMIS stations reveals that ET captures 94% of the total weather variability.

[c] Fraction of residents reporting at least some college education.

Summary statistics under water budgets are shown by marginal consumption block in Table 3. The table shows that marginal consumption is within a household's water budget (block 1 or 2) in 82% of the observations.[18] Only 18% of the observations have marginal consumption in block 3 or 4. The table shows that household consumption increases with the marginal block but water budgets do not: water budgets are largest for block 2 consumers and smallest for block 1 and 4 consumers. The large water budgets associated with block 2 consumption appear to be explained by higher ET and irrigated area, whereas the household size is slightly below average. Block 3 and 4 consumers appear to be somewhat wealthier and thus perhaps less sensitive to the higher prices in those blocks; consequently they may be less inclined to make an effort to better match their water use with their water budgets.

[18] This does not imply that 82% of households always consume within their water budgets. Marginal consumption for a given household tends to move across blocks through time.

Table 3: Summary statistics under water budgets by marginal consumption block.[a]

Variable	Full Sample	Block 1	Block 2	Block 3	Block 4
Fraction of observations	1.00	0.26	0.56	0.15	0.03
Consumption (CCF/month)[b]	16.92	6.26	17.88	27.05	37.97
Water budget (CCF/month)	25.84	20.69	29.52	22.41	20.34
ET (in/month)	5.03	4.34	5.33	5.17	4.81
Budget (2010$/year)	310.27	299.89	312.08	319.39	319.11
Household size (#)	3.53	3.60	3.48	3.53	3.60
Irrigated area (sq-ft)	4176.95	3481.27	4753.42	3364.07	3700.60
Education[c]	0.50	0.49	0.49	0.52	0.52

[a] Includes 569,730 observations. Average consumption and ET values for the full sample are above annual means because the sampling period (April 2009 – September 2012) includes a relatively larger share of warmer, drier months. Block-weighted averages may not match full sample averages due to rounding error.

[b] CCF = hundred cubic feet.

[c] Fraction of residents reporting at least some college education.

Parameter Estimation

Similar to Baerenklau et al. (2014a), I use maximum likelihood to derive estimates of $\{\alpha, \beta, \gamma, \sigma_\varepsilon, \sigma_\eta\}$ that identify the semi-log demand system equations in table 1. A notable innovation is that I include household-level fixed effects in this estimation. To do this, I first use the 2003-2008 data under uniform pricing to derive a mean prediction error for each household. I then use these mean prediction errors as proxies for persistent unobserved household heterogeneity that presumably affects consumption under block rates, as well.[19] Parameter estimates and standard errors are shown in table 4 (continued on the next page).

Table 4: Block-rate model parameter estimates and standard errors.

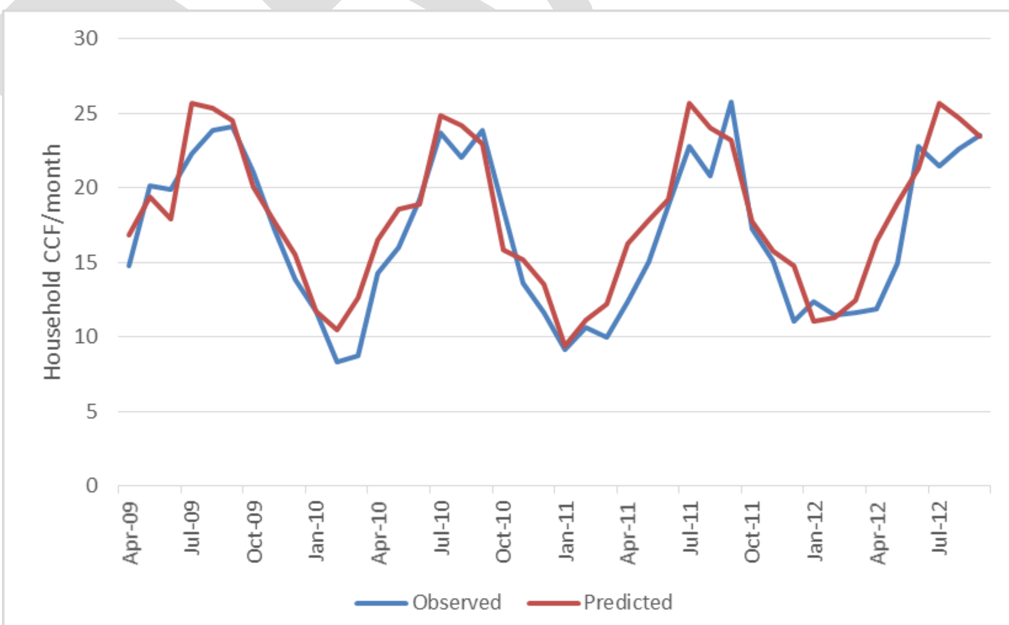
Variable	Description	Estimate (Std Err)
Constant	Constant	1.5550 (0.0080)
Education	Fraction of census tract residents reporting "at least some college" or more education	0.5556 (0.0076)
HHS	Household size (# of persons)	0.1347 (0.0007)
IA	Irrigated area (1000 sq ft)	0.0295 (0.0002)
Spring	Dummy for Apr-Jun	0.2335 (0.0046)

[19] Thanks to Professor Richard Carson for suggesting this.

Summer	Dummy for Jul-Sep	0.5185 (0.0057)
Fall	Dummy for Oct-Dec	0.4670 (0.0033)
Conserve	Dummy for conservation request	-0.1350 (0.0070)
ET	ET (in/month)	0.1140 (0.0013)
Time trend	Linear annual increments	-0.0727 (0.0009)
Fixed effect	Household-level fixed effect	1.1106 (0.0028)
p_{it}	Real price	-0.2201 (0.0019)
d_{it}	Real money budget	0.0001 (8e-7)
σ_ε	Standard deviation for ε	0.5676 (0.0015)
σ_η	Standard deviation for η	0.2386 (0.0012)

The estimation results are generally very good. Signs are intuitive and significance levels are high (due in part to the large number of observations). The magnitudes for the seasonal dummies also are intuitive, which is an improvement upon Baerenklau et al. (2014a). Figure 2 shows the in-sample predictive ability of the model which exhibits good fitness.

Figure 2: Observed vs. predicted average monthly household usage under block rates.



Welfare Calculations

Welfare analysis focuses on the last twelve months of data (October 2011 – September 2012), during which time the demand reduction due to allocation-based rates was estimated by Baerenklau et al. (2014b) to have reached its apex. To establish a baseline from which to compare the effects of alternative water conservation policies, I use the estimates in Table 4 to derive expected consumption levels, utilities, expenditures, and agency revenues from water sales during 2011-12 under the 2008 uniform price policy. Numerical integration is accomplished with Gauss-Hermite quadrature. Next I derive the same quantities under EMWD's allocation-based rates, using 2008 prices as the reference for measuring expenditures. I then do the same for four alternative policies that achieve the same estimated reduction in usage compared to the baseline: (1) a proportional increase in 2008 prices; (2) a proportional increase in 2008 prices with a uniform lump-sum return of excess revenues (compared to those collected under allocation-based rates); (3) a uniform quantity restriction with no change in 2008 prices; and (4) a uniform quantity restriction with no change in 2008 prices and with a uniform increase in the daily service charge to cover revenue shortfalls. Table 5 summarizes the results of these simulations.

Table 5: Equivalent variation statistics for five alternative policies

	Allocation-based rates	**Price increase**	**Price increase with lump sum rebate**	**Quantity restriction**	**Quantity restriction with fixed cost increase**
Minimum EV ($/month)	-170.93	-150.97	-139.95	-7.26	-16.41
Mean EV ($/month)	1.98	-15.29	-7.40	-0.61	-7.26
Median EV ($/month)	5.70	-13.73	-5.82	-0.52	-7.16
Maximum EV ($/month)	168.28	-0.99	7.10	-0.04	-6.69
# of better-off households	8455	0	2298	0	0
% of better-off households	62%	0%	17%	0%	0%
Mean equivalent variation ($/month) by income terciles					
Top third	4.99 (1.4%)	-15.78 (-4.4%)	-7.90 (-2.2%)	-0.60 (-0.2%)	-7.24 (-2.0%)
Middle third	2.51 (0.8%)	-14.69 (-4.6%)	-6.78 (-2.1%)	-0.59 (-0.2%)	-7.23 (-2.3%)
Bottom third	-1.57 (-0.6%)	-15.42 (-5.5%)	-7.51 (-2.7%)	-0.65 (-0.2%)	-7.30 (-2.6%)

Compared to the baseline policy, each of the policies in table 5 reduces water demand by around 17%. Perhaps the most distinguishing characteristic of the allocation-based rate structure is that it slightly improves overall welfare (positive mean EV) compared to the baseline policy. Under each of the other policies, overall welfare declines as consumption is reduced. Under allocation-based rates, 62% of households are made better-off while 38% are made worse-off. The only other policy that improves welfare for at least some households is the price increase with lump sum rebate, which makes 17% of households better-off even though overall welfare declines. However another distinguishing characteristic of allocation-based rates is that they produce the largest variability in welfare effects, which may not be perceived by water utilities as a desirable attribute.

The bottom section of table 5 shows the mean welfare effects by income tercile. The numbers in parentheses express these effects as percentages of the monthly money budget. All of the policies except for the quantity restriction appear to be somewhat regressive. The allocation-based rates increase welfare by 1.4% among households with incomes in the top tercile and reduce welfare by -0.6% among households with incomes in the bottom tercile. However each group is better-off than it would be under either of the two fiscally neutral policy alternatives.

To better understand the distribution of welfare across the sample households under each policy, I estimate ordinary least squares regressions of household equivalent variation on a constant, income, water consumption prior to the rate change, and water use efficiency prior to the rate change. Efficiency is measured as the ratio of a household's consumption to its water budget, so higher values correspond to less efficient households. Table 6 summarizes the coefficients from these regressions (all coefficient estimates are significant at the 1% level).

Table 6: Equivalent variation regression coefficients across policies.

	Allocation-based rates	**Price increase**	**Price increase with lump sum rebate**	**Quantity restriction**	**Quantity restriction with fixed cost increase**
Constant	-26.4059	-14.3333	-6.3713	-0.8748	-7.5571
Income	0.1152	0.0384	0.0386	0.0028	0.0030
Consumption	-0.1566	-0.6683	-0.6741	-0.0342	-0.0361
Efficiency	-5.1170	0.3707	0.3408	0.0659	0.0910

As before, the allocation-based rate structure is noticeably different from the other policies: it is the only policy under which the induced welfare change is positively (and strongly) correlated with water use efficiency. In other words, more efficient households tend to "do better" than less efficient households under allocation-based rates, while the reverse holds (though more weakly) for the alternative policies. Under all policies, lower usage households tend to "do better" than higher usage households; and again the mildly regressive nature of these policies can be seen in the small but positive coefficients on income.

Discussion and Conclusions

This article presents a theoretically consistent methodology for estimating welfare change under block rate pricing and applies it to a 2009 rate structure change by the Eastern Municipal

Water District of Southern California that achieved significant reductions in overall water demand (Baerenklau 2014a). I find that the allocation-based block rates adopted by EMWD increased the welfare of the sample households by an average of $24 annually; however the average welfare of households with incomes in the lower tercile was reduced slightly, implying that the policy is somewhat regressive. Nonetheless, out of 13,565 sample households, 8455 were made better-off by the policy.

The welfare effects of allocation-based rates appear to be structurally different from those induced by uniform price and quantity policies in multiple ways. First, both price and quantity policies that achieve the same levels of consumption and revenue as under EMWD's allocation-based rates tend to decrease overall welfare. A price policy that returns to each household an equal share of excess revenues can make some households better-off, but overall welfare still declines. Second, both price and quantity policies tend to impinge (in a welfare sense) upon larger water users regardless of their usage efficiencies; whereas allocation-based rates tend to impinge upon both larger users and more inefficient users regardless of their water use levels. Using the same dataset, Baerenklau et al. (2014b) find that policy-induced water demand reductions also were largest among the most inefficient users; thus allocation-based rates appear to target more inefficient users in multiple ways.

Results for the quantity restriction policies show that the induced welfare changes under these policies tend to be smaller and have the smallest variability across the sample households. Although more costly overall, these may be desirable instruments for water utilities that prefer egalitarian policies that avoid imposing large welfare losses on subsets of customers.

One unexpected result from the policy simulations is that the uniform quantity instruments perform better than the uniform price instruments: the quantity restriction with fixed cost increase is, on average, around $2 better per year than the price increase with lump sum rebate. Preliminary sensitivity analyses indicate that this may be due to the stochastic elements of the model: setting the variances of both error terms equal to zero produces the more intuitive result that aggregate welfare under the price instrument is higher than under a uniform quantity restriction. However these differences are small, and the stochastic elements of the model play important roles in the simulations, so additional work is needed to verify this.

From a methodological standpoint, the approach suggested by Strong and Smith (2010) appears to work well in practice and enables analysis of welfare changes at the household under block pricing. The DCC model remains useful and appropriate for generating the parameter estimates needed to undertake structural welfare estimation so long as the underlying direct utility function is known. The methodology is general and could be applied to any instance of block rate pricing with appropriate data; however declining block rates may present additional challenges not addressed here including the possibility of multiple utility-maximizing bundles due to nonconvexities in the budget set.

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