Solving the West's Water Problems*

by

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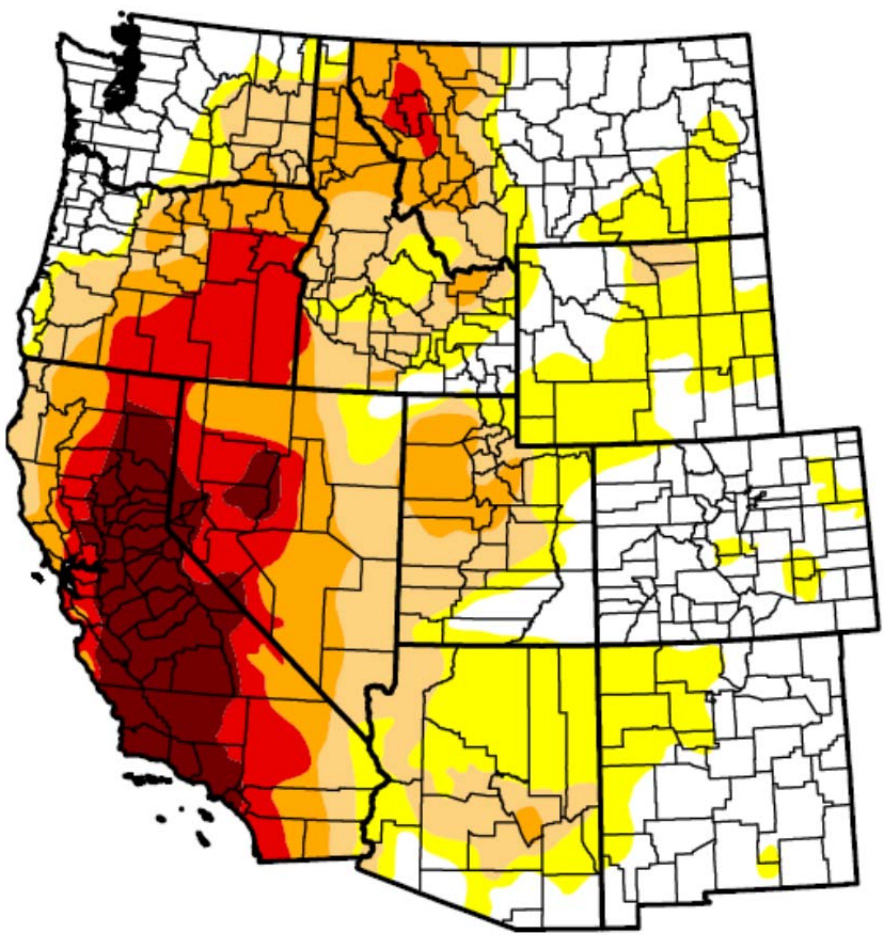
Motivation for Lecture

Increasing evidence that existing water infrastructure and institutions in Western United States are inadequate to meet current and future demand



December 29, 2015

(Released Thursday, Dec. 31, 2015)

Valid 7 a.m. EST

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	33.17	66.83	45.07	29.30	15.92	6.85
Last Week *12/22/2015*	31.80	68.20	46.35	32.08	16.71	6.85
3 Months Ago *9/29/2015*	22.77	77.23	57.81	42.42	26.50	7.62
Start of Calendar Year *12/30/2014*	34.76	65.24	54.48	33.50	18.68	5.40
Start of Water Year *9/29/2015*	22.77	77.23	57.81	42.42	26.50	7.62
One Year Ago *12/30/2014*	34.76	65.24	54.48	33.50	18.68	5.40

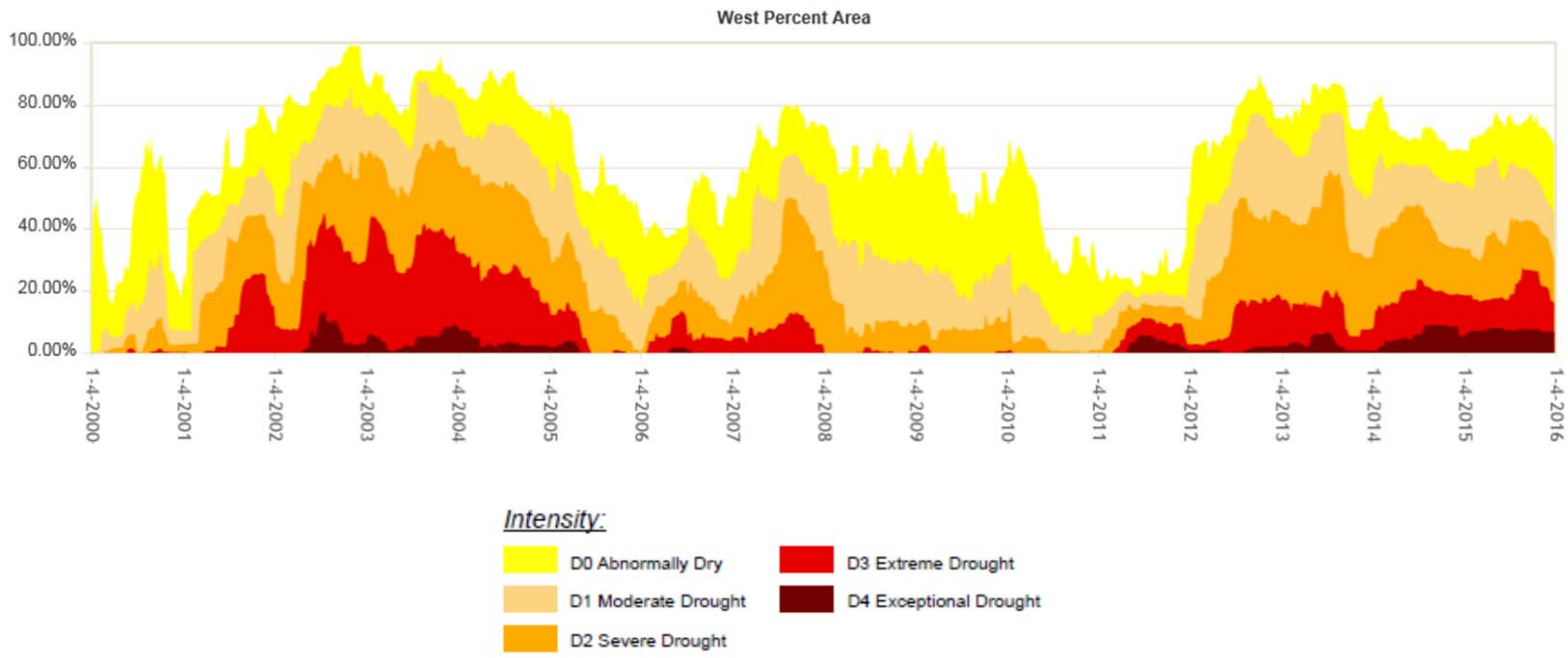
Intensity:

- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

Source: http://droughtmonitor.unl.edu

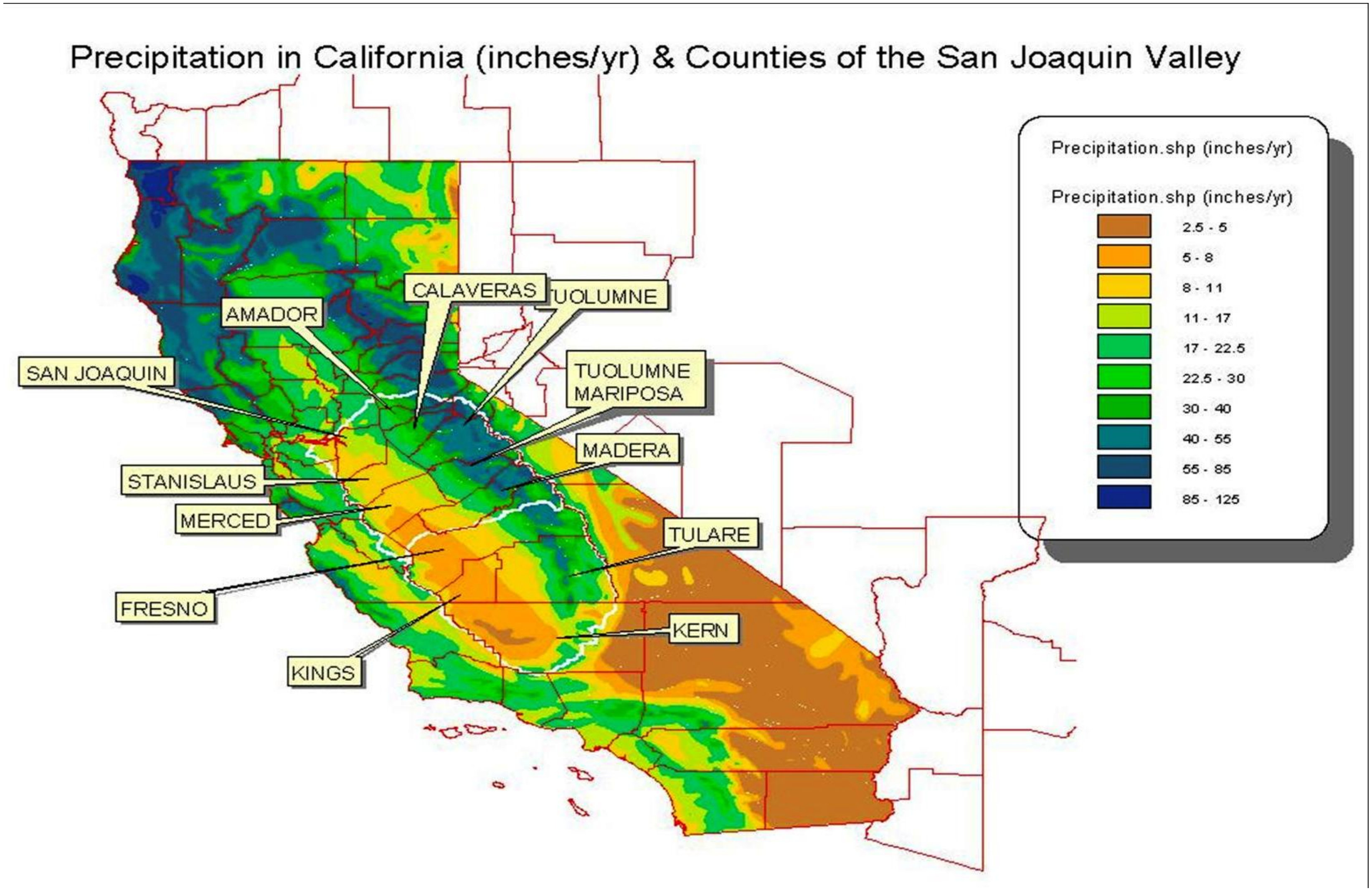
Recent History of "Drought" Conditions in the West



Source: http://droughtmonitor.unl.edu

California's and the West's Water Challenge

(Water is not where people live)



Water Infrastructure

(Move water to where people want it)

The West's Wholesale Water Supply Problems-1

1) No major water storage or delivery infrastructure completed in West since early 1970s

Example: California's Major Water Infrastructure Projects

All-American Canal--Constructed in 1930s
Colorado River Aqueduct--Completed in 1941
Los Angeles Aqueduct--Completed in 1913.
Mokelumne Aqueduct--Completed in 1929. Second aqueduct completed in 1949.
San Francisco Hetch Hetchy Project--Completed in 1923
Central Valley Project--Constructed in 1930s - 1950s.
State Water Project--Constructed in 1960s – early 1970s

Population of California in 1970 was roughly one-half of current value of 38.8 million

Similar rates of population growth in rest of the west between 1970 and the present time

The West's Wholesale Water Supply Problems-2

2) Extremely high transactions costs associated with trading water

Legal Barriers to Water Trading

Water is a "usufruct" property right (cannot own water), but only own "right to use it"

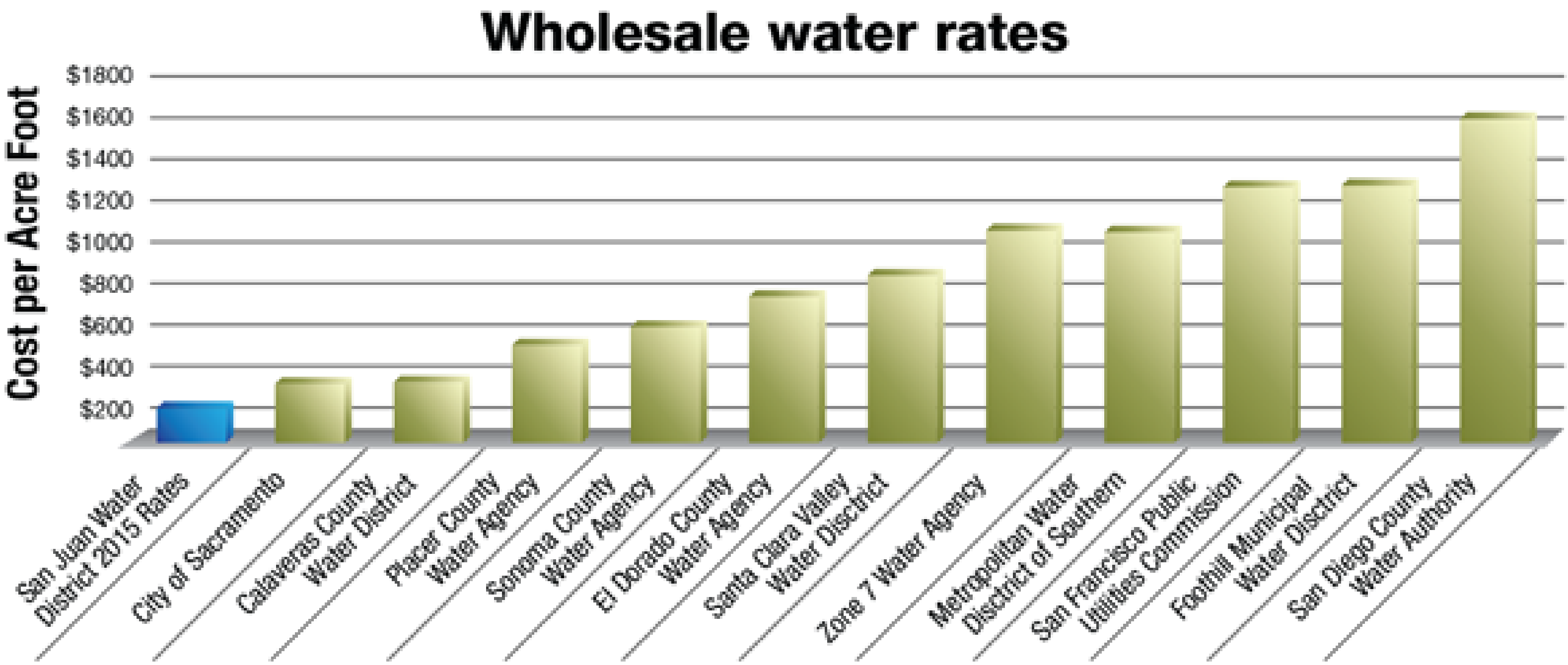
Owner can lose "usufruct" right if water is not put to beneficial use

Costly legal process required to trade water, particularly with entity outside of watershed (for example, agricultural to urban transfer)

A trade can only take place if parties can demonstrate that no existing water rights holders are harmed by water transaction

The West's Wholesale Water Supply Problems-3

3) Massive spatial differences in wholesale water prices, particularly for agricultural versus urban users



The West's Retail Water Supply Problems-1

1) Increasing need to implement conservation measures to manage "drought" conditions by urban water distribution utilities
    1) In Spring of 2015, Governor of California issued an executive order to reduce urban water consumption statewide by 25% relative to 2013 level

2) Increasing frequency of revenue shortfalls relative to costs for urban water utilities (typically more than 85% of costs do not vary with volume of water sold)
    1) California Public Utilities Commission reports 5 out of 11 water utilities had revenue shortfalls greater than 20 percent of allowed revenue requirement in 2010
    2) 11 out of 32 utilities had revenue shortfalls greater than 10 percent of allowed revenue requirement in 2010
    3) Largest frequency and magnitude of shortfalls occurs for utilities with the least number of customers

The West's Retail Water Supply Problems-2

3) Increasing temporal mismatch between prices consumers are charged and their need to reduce water consumption
    1) Utilities with revenue shortfalls in current period typically recover these shortfalls in future periods through rate increases or surcharges
    2) Under-recovery creates need to amortize revenue shortfalls
        a) Interest rate charged can significantly impact customer's bill
    3) Significantly reduces utility's incentives to reduce production costs

Water Revenue Adjustment Mechanism (WRAM) set by California Public Utilities Commission (CPUC) imposes a surcharge on customers in future months to recover past revenue shortfalls

1) According to CPUC, WRAM increased customer's monthly water bill by as much as 40 percent in 2010

"Why are ratepayers being penalized with higher rates {now} for conserving water {in the past} as their utility has directed them to do?"

--California State Senator

California-Specific Retail Water Problems

California has legal restrictions on how prices and increasing block pricing can be used to encourage conservation

California Proposition 218 (Right to Vote on Taxes Act)

1) Passed in response to Proposition 13
1) Fees charged for municipal services, such as water delivery, cannot exceed the cost of providing service
2) Citizens of San Juan Capistrano recently filed and won lawsuit claiming that the increasing block pricing plan they face violates Proposition 218

AB 2882 attempts to clarify Proposition 218 to allow increasing block pricing of water

1) Further legislation and legal wrangling likely to allow increasing block pricing to be used to encourage water conservation

Towards Solving the West's Water Problems

Two approaches for Western United States to meet future water demand

1) Manage existing water resources, primarily through wholesale market mechanisms and retail pricing
2) Build and pay for additional water storage and/or transportation infrastructure

Lecture discusses two lines of research that attempt to provide solutions

1) Wholesale water market that prices all relevant physical, environmental, and institutional constraints
2) Estimate customer-level model of urban water demand that can be used to
    1) Design nonlinear price schedules to achieve region's water pricing goals (conservation, environmental, equity, etc.)
    2) Measure economic benefits of proposed water infrastructure investments (consumers' aggregate willingness to pay)

A Locational Marginal Pricing (LMP) Wholesale Market for Water

Hydrology and Water Trading

Hydrology of water re-charge and water flow implies that injecting an acre-foot now may not be equivalent to withdrawing an acre-foot later at the same location

Same statement applies to an injection at one location and withdrawal at another location at the same time

Injections and withdrawals at different points in time and/or different locations can also have adverse environmental impacts

Harm to fish and wildlife

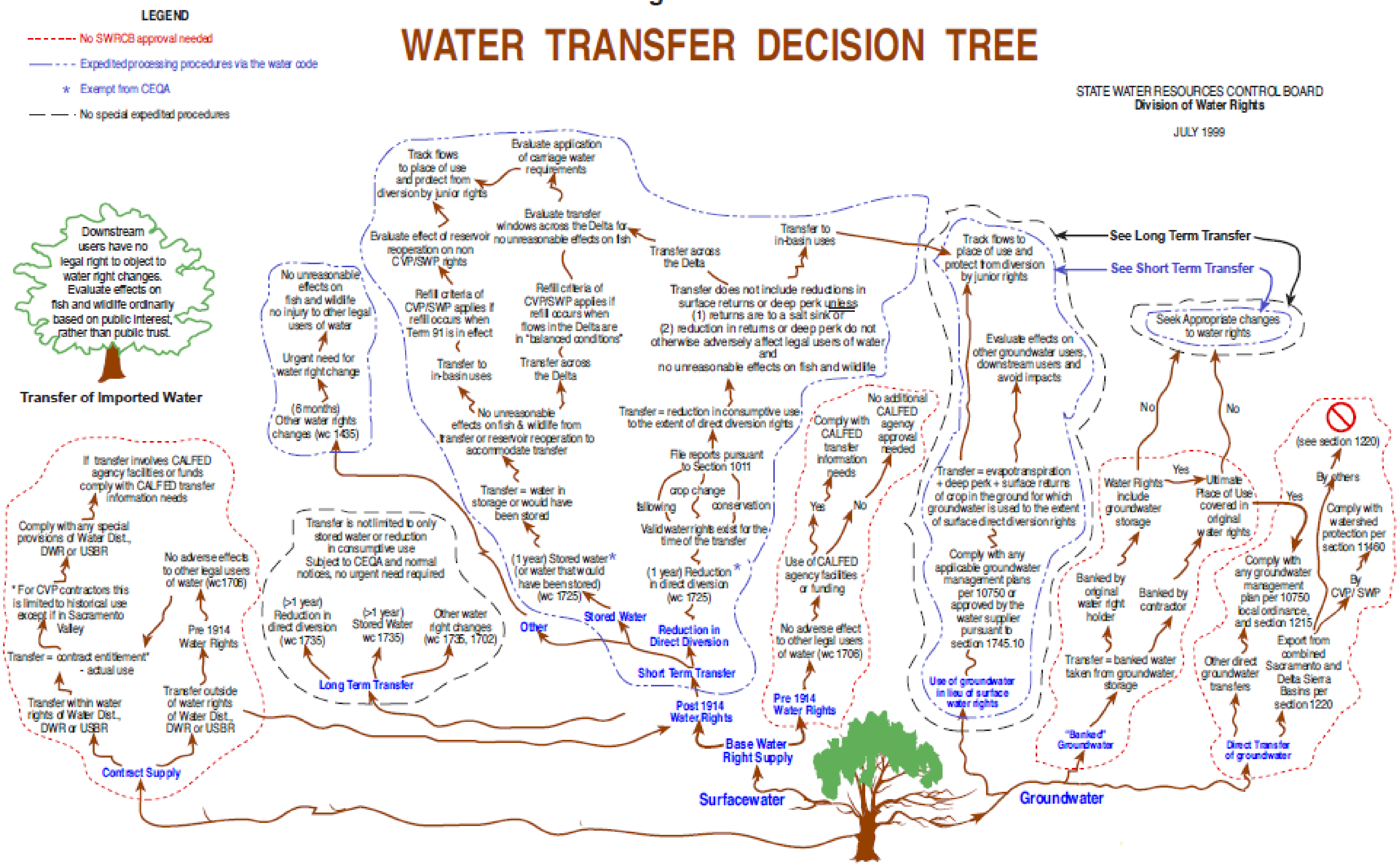
Water transfer can adversely impact the ability of other water rights holders to exercise their water rights

Water trades typically occur on a bilateral basis

Two parties wishing to trade must address environmental impacts and 3rd party effects through a lawyer-intensive administrative process

Figure 1

WATER TRANSFER DECISION TREE



Source: “A Guide to Water Transfers,” SWRCB

Electricity and Water Parallels

Electricity Supply Industry re-structuring offers several important lessons for design of wholesale water markets

1) Create Independent System Operator (ISO) for major California water storage and delivery network
2) Use locational marginal pricing (LMP) to set prices and schedule deliveries from CA storage and delivery network

Historically, wholesale electricity trading looked a lot like wholesale water trading

1) Only bilateral transactions that occurred did not harm ability of existing owners of transmission infrastructure to deliver their energy
2) Limited volume of transactions and typically only those that benefitted incumbent vertically integrated utilities
3) Mansur. E.T. and White M.W, (2012) "Market Organization and Efficiency in Electricity Markets" documents enormous increase in trading volume for same physical transmission network that results from establishing a formal wholesale market with LMP pricing

Physics and Electricity Trading

Underlying physics of electricity flows implies that injecting 1 MWh at one location may not allow withdrawal of 1 MWh at another location

1) Transmission congestion
2) Transmission losses
3) Inertia of generation units
4) Non-convexities in generation unit operation

Failure to account for all physical operating constraints in wholesale market pricing mechanism has led to substantial market inefficiencies

Particularly in the US, which has significantly less transmission capacity to major load centers than other industrialized countries and in regions with a larger share of intermittent renewable generation resources

Market Solution for Electricity

Electricity supply industry handles operation of transmission network with many suppliers and demanders using an independent system operator (ISO)

1) All market participants have equal access to transmission network according to rules approved by relevant regulatory body
2) These rules or tariff are developed through a stakeholder process
3) All physically feasible trades are allowed subject to tariff

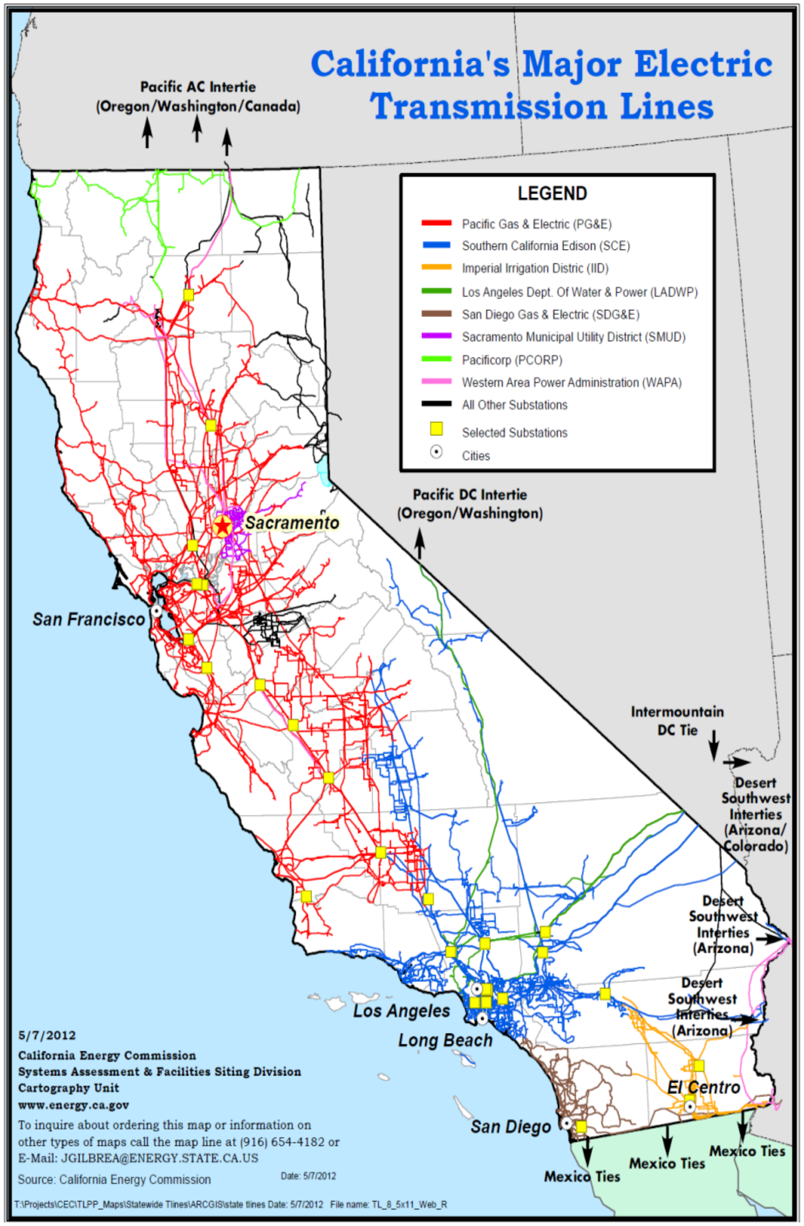
Which locational offers and bids are accepted depends on configuration of transmission network and other relevant operating constraints on transmission network and generation units

ISO must maintain supply and demand balance at all locations in the transmission network

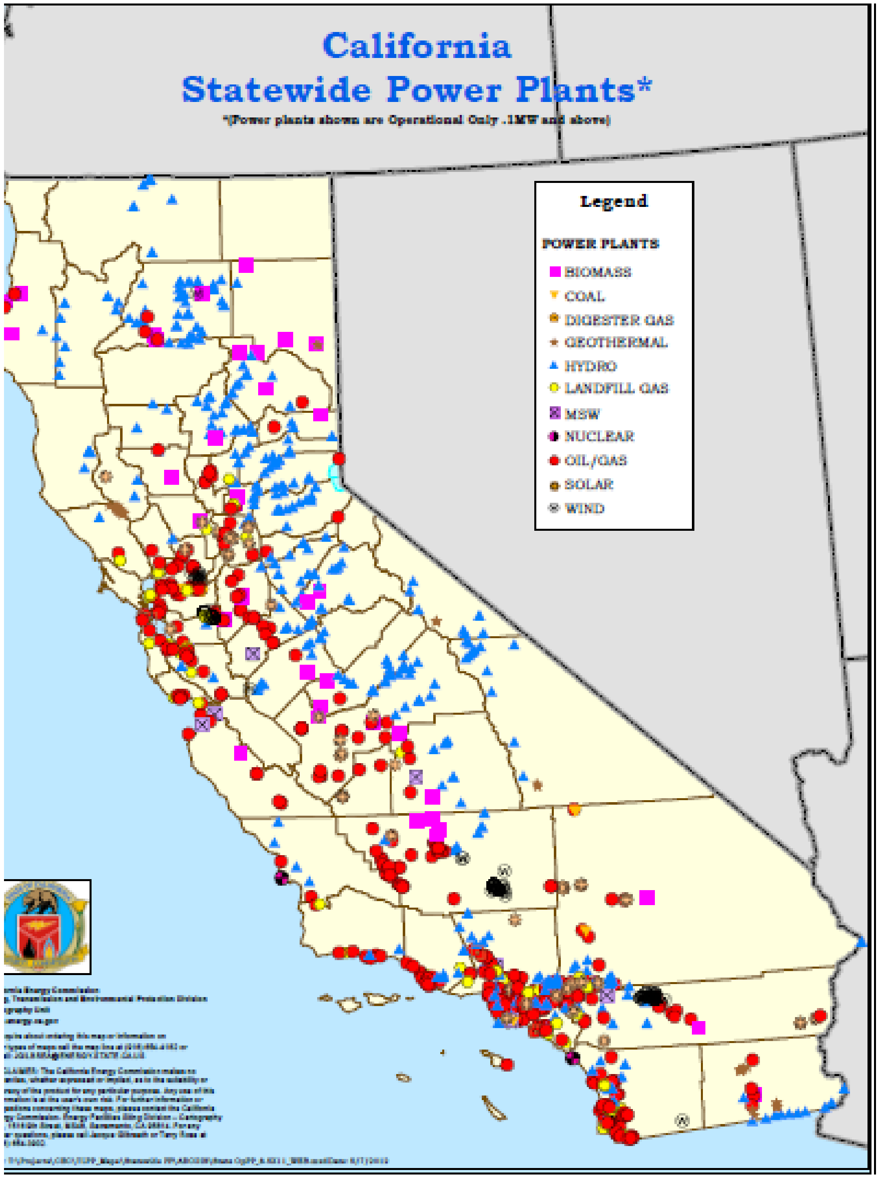
Multiple forward markets operate before actual production and consumption occurs

Day-ahead forward market and real-time imbalance market and each respects same network operating constraints to determine accepted bids and offers

Parallel Networks—Water and Electricity



Parallel Resources—Water and Electricity



Locational Marginal Pricing—Generalizes computation of equilibrium prices by solving an optimization problem

Producers submit offer (willingness to supply) curves that are step functions (p_{ij},q_{ij}) i=1,2,..K (number increments and j=1,2,…,J (number market participants)

p_{ij} = offer price for increment i of supplier j

q_{ij} = offer quantity for increment i of supplier j

Suppose consumers submit bid (willingness to purchase) curves that are step functions $Q_j - SN_j(p)$

Q_j = Demand at price of zero for consumer j

$SN_j(p)$ = "nega-watt:" supply curve for consumer j

Market-clearing price computed from solution to

$$\min_{\{0 \le x_{ij} \le q_{ij}\}} \sum_{j=1}^{J} \sum_{i=1}^{K} p_{ij} x_{ij} \quad s.t. \sum_{j=1}^{J} Q_j = \sum_{j=1}^{J} \sum_{i=1}^{K} x_{ij}$$

and is Lagrange multiplier for supply equals demand constraint

Locational Marginal Pricing

Minimize as-offered cost, $\sum_{j=1}^{J}\sum_{i=1}^{K} p_{ij}x_{ij}$, to serve demand at all locations or nodes in transmission network subject to transmission capacity constraints and losses and all other relevant operating constraints

These contraints typically take the form of linear equality and inequality constraints on elements of x_{ij}

Locational marginal price is equal to change in optimized objective function value, minimum value of as-offered cost, associated with withdrawing an additional MWh at that location or node in network

1) *LMPs reflect impact of all constraints associated with withdrawing one more unit at a location*
2) *Any operating constraint that can be represented mathematically can be priced*

LMPs reflect scarcity conditions at a location in network

Supplier can be paid more than their willingness to sell because they own a scarce resource

Application to Water Markets

Run market for water injections and withdrawals over space and time accounting for man-made and natural hydrological network constraints

Stakeholders agree to a tariff specifying all relevant operating constraints and market rules for a given "water transmission and storage network"

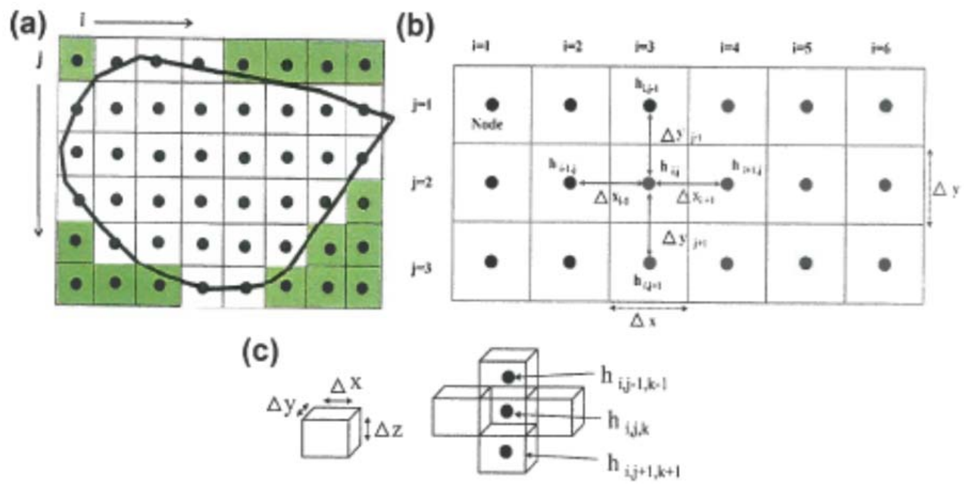
- All feasible trades can occur subject to market rules

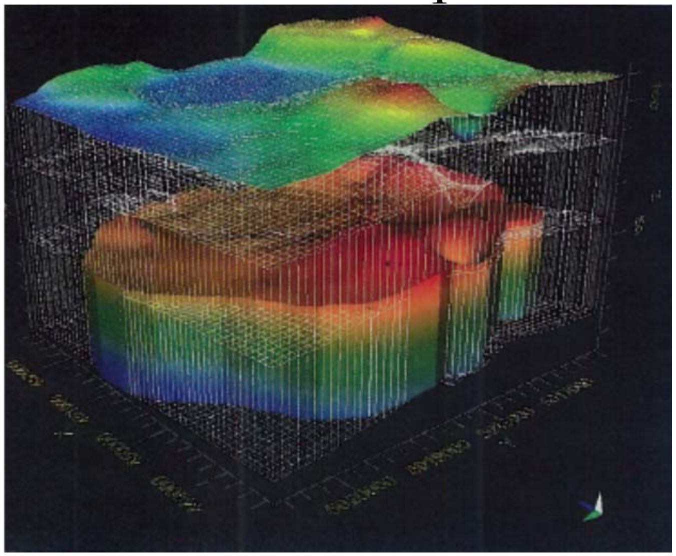
Market prices can be determined over space and time by minimizing as-offered cost of meeting demand over space and time subject to these "water network" and other relevant operating constraints

- Locational marginal price of water is increase in minimized value of as-offered cost subject to increase in demand at a given point in space and time
- Potentially a different price set for a each location at a given point of time in the future
  - *Can run monthly, weekly, or even daily markets*

Water Network Model

Flows across cubes can be modeled as large linear difference equation





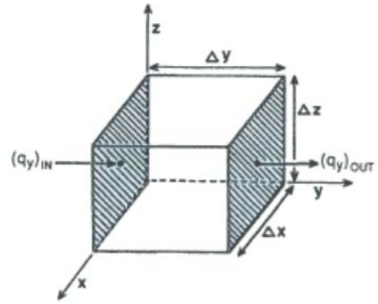


Figure 3.1 Representative elementary volume ($\Delta x \Delta y \Delta z$) showing the components of flow along the y-coordinate axis.

Current Research

Mathematical model of actual water network, set of linear equality and inequality constraints, to implement LMP pricing market

California has a number of water banks, which are essentially small water markets, typically within a single water basin

Use data from water bank to illustrate potential increase in volume of feasible trades and economic benefits from implementing LMP pricing relative to current water allocation mechanism

- Model hydrology of water system
- Environmental constraints
- Political constraints

Compare set of trades and prices that actually occurred with set of feasible trades and prices that result from applying LMP pricing mechanism and modeling all relevant operating constraints

Conclusions from Research on LMP Wholesale Market for Water

Market mechanisms facilitated by ISO can manage increasing water scarcity at least cost

1) Captures economies to scale in transactions costs for water trading by concentrating them in up-front tariff-setting process and then amortizing them over all physically feasible transactions rather than paying for each bilateral transaction

Eliminates large spatial wholesale water price differences except when there is a hydrological, environmental, legal constraint that is binding

Allows market mechanisms to be run over large geographic areas and long time horizons into future

LMP is being successfully used to deliver benefits in other markets

Wolak, F.A. (2011) "Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets, *American Economic Review*, May, 247-252.

An LMP market has the potential to deliver even proportionally greater benefits in water sector

Measuring the Customer-Level Demand for Water under Nonlinear Pricing

Motivation for Research

Uncertainty about structure of customer-level demand and the distribution of customer-level demands considerably complicates utility's pricing problem

Unknown heterogeneity in customer-level demand and price responsiveness based on customer characteristics increases utility's uncertainty in sales and revenues

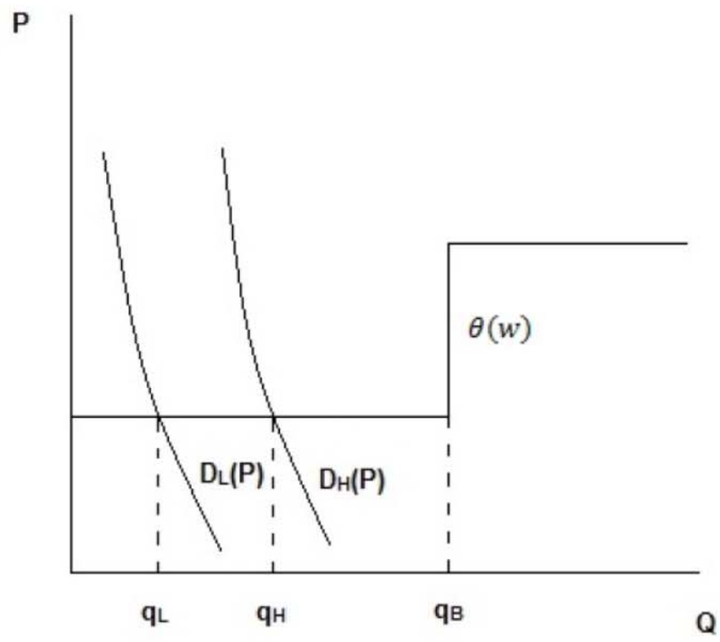
Model of customer-level of demand and estimate of distribution of customers in utility's service territory can be used to design nonlinear tariffs to achieve conservation or other pricing goals

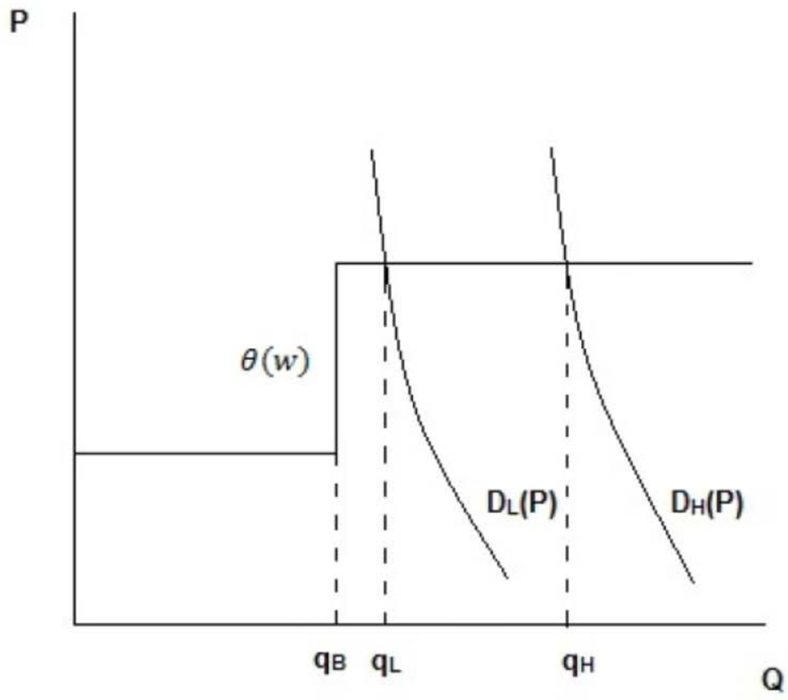
Limits need for Water Revenue Adjustment Mechanisms that leads to price increases in future periods

Accurate estimates of customer-level demand and distribution of demand within region is necessary to assess economic benefits associated with a proposed water extraction, storage, or delivery infrastructure investment

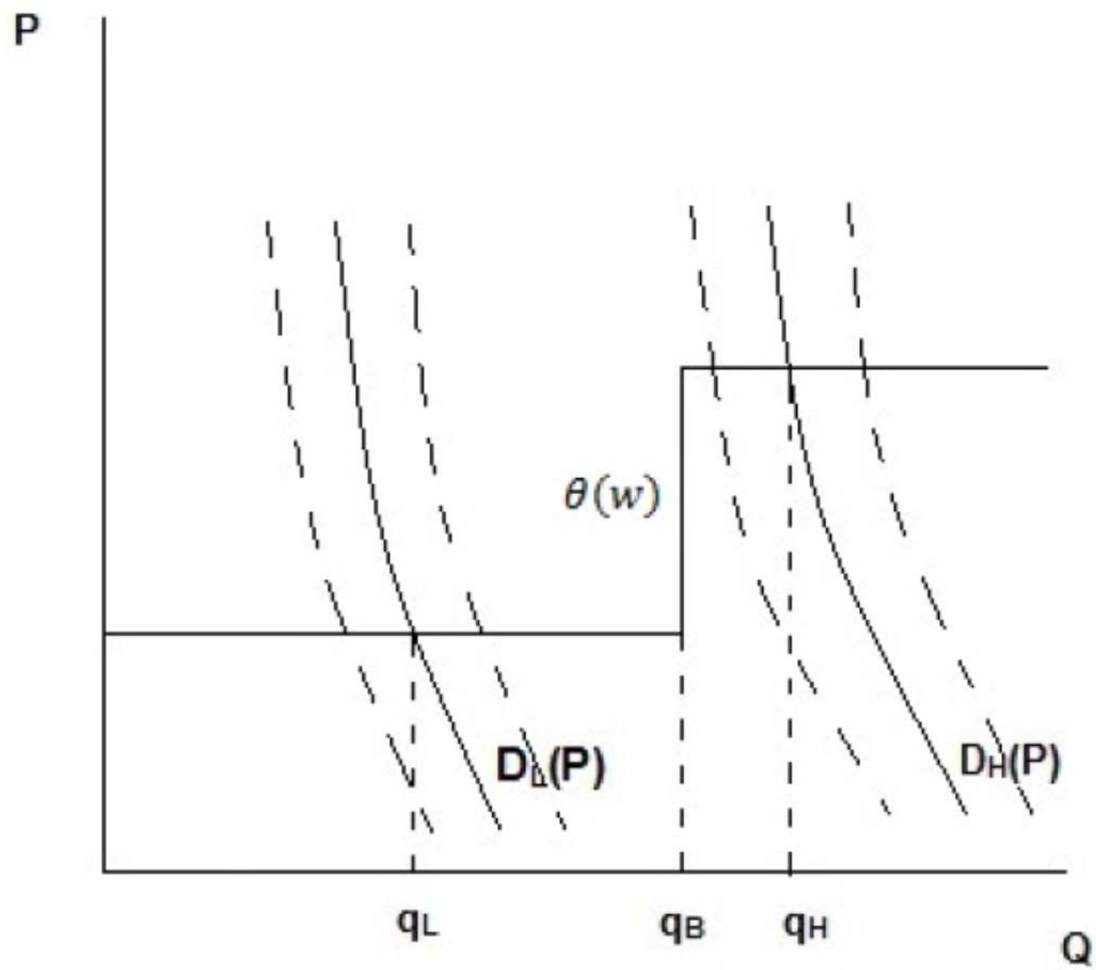
Customers' willingness to pay for water services provided by project used to quantify benefits of infrastructure investment

Setting Nonlinear Price Schedules





Setting Nonlinear Price Schedules



Current Goals of Research

Estimate household-level model of the demand for water under increasing block pricing that accounts for

1) monthly weather variation
2) potentially observed customer-level heterogeneity
3) characteristics of vegetation on customer's lot
4) unobserved heterogeneity

Use model and distribution of customer-level demographic characteristics in utility's service territory to compute distribution of aggregate water demand for any possible price schedule

1) Yields estimate of distribution of total utility-level water sales and revenues for any arbitrary nonlinear price schedule
2) Can use model to design rates to achieve any set of rate design goals for utility

Outline of Presentation

1) Description of datasets used in analysis

2) Model of water demand with nonlinear prices

3) Derivation of log-likelihood function (with demographics)

4) Water sales and revenues for arbitrary price schedules

5) Optimal rate design using models

6) Comparative test of alternative demand models

Four Data Sources Used in Analysis

1) Customer-level consumption at the *billing cycle-level*, customer's Zip Code, form of nonlinear price schedule faced by household, and other information necessary to compute customer's monthly water bill

Start date and end date of billing cycle for each customer for at least one year's worth of billing cycles

Start date within month and length of each billing cycle differs by customer

2) Daily weather variables—rainfall and temperature—used to compute billing cycle-level monthly *weather exposure variables specific to each customer*

1) Average daily maximum temperature during billing cycle

2) Total rainfall during billing cycle

Four Data Sources Used in Analysis

3) The distribution within customer's Zip Code of customer-level demographic variables from US Bureau of Census Public Use Microdata Sample (PUMS) of American Community Survey

1) For each Public Use Microdata Area (PUMA) we have demographic characteristics of all households surveyed in that PUMA and sampling weight for household demographic characteristics sampled

2) PUMAs can be matched to Zip Codes so that a distribution of household-level demographic variables in Zip Code is available for all Zip Codes in utility service territory

Above information available for a number of water utilities throughout the United States with a variety of weather conditions and zip code-level distributions of customer-level demographic characteristics

Four Data Sources Used in Analysis

4) NASA compiles information on vegetation at 30 x 30 meter level of resolution for entire United States (every two months)

Normalized Difference Vegetation Index (NDVI) defined on interval (-1,1)
Values close to -1 are typically water
Values close to zero (-0.1 to 0.1) are typically rock, sand, or snow.
Values in the interval (0.2 to 0.4) are typically shrub and grassland
Values close to 1 typically indicate temperate and tropical rainforests

Link NDVI value to household's address using GPS and incorporate value of NDVI in level of demand, price coefficient, and income coefficient in demand model

Real World Example of NDVI Comparison

(NDVI Above Road = 0.306 and NDVI Below Road = 0.326)

Utilities Under Consideration in Research

Valley of the Moon (near Sonoma), California (Today)

Cobb County, Georgia

Tacoma, Washington

Have data from a number of other utilities in US and can always use data from more utilities in different regions of West.

Phoenix, Arizona

Santa Rosa, California

Washington, DC

Monterey, California

Mathematical Structure

Let $U(x,w|A,Z,V,\varepsilon,\beta)$ equal the utility function for a household over the N-dimensional of vector of goods, $x = (x_1,x_2,\ldots,x_N)$, where x_k is the household's monthly consumption of good k, and monthly consumption of water, w.

The utility function also depends on the household's demographic characteristics A, a vector of weather variables Z, value of NVDI index V, a vector of unobserved characteristics ε, and is parameterized by the vector β. Let p_k equal the price of the kth element of x, $x_{k.}$ Let θ(w) equal the nonlinear price function that the household faces.

If a household purchases w* units of water during the month then its total bill is equal to $R(\theta(w)) = \int_0^{w*} \theta(s)ds,$ which is equal to the area under the nonlinear price schedule up to the observed consumption level, w*, including monthly fixed charge, F.

Mathematical Structure

A household that consumes w units of water and the vector of other goods, x, has a monthly spending equal to $\sum_1^N p_i x_i +$ R(θ(w))

Household's observed choices of x and w are assumed to be the solution to the following optimization problem:

$max_{x \geq 0, w \geq 0} \mathrm{U}(\mathrm{x}, \mathrm{w} | \mathrm{A}, \mathrm{Z}, \mathrm{V}, \varepsilon, \beta)$ subject to $\sum_{i=1}^N p_i x_i +$ R(θ(w)) = M,

where M is the household's monthly income. (Note that M is an element of A, vector of household's demographic characteristics.)

Solving this problem yields the household's utility-maximizing choices for x and w as a function of the vector of prices, P = $(p_1, p_2, \ldots, p_N)$ of the N other goods; the nonlinear price function, θ(w); and monthly income, M.

Mathematical Structure

$w^*(P,\theta,M,A,Z,V,\varepsilon,\beta)$ is the solution to household's problem.

P = Demand depends on the prices of other goods

$\theta(w)$ = the nonlinear price schedule for water,

M(A) = the household's monthly income,

A = the vector of observed characteristics of the household,

ε = vector of unobserved (to econometrician) characteristics of the household,

Z = vector of weather variables,

V = Vegetation index (NDVI)

β = parameters of the household's preference function

Assuming a density for ε, $f(\varepsilon|\delta)$, can derive the density of the household's observed water consumption, w,

$$g(w\,|P,\theta,A,Z,V,\beta,\delta)$$

which also equal to the likelihood function conditional on A.

Log-Likelihood Function

The log-likelihood function is equal to

$$L(W|\beta,\delta) = \sum_{s=1}^{S} \ln[\sum_{n=1}^{N(s)} wt(s,n) \prod_{t=1}^{T(s)} g(w_{st} \,|P_{st}, \theta_{st}, A_{sn}, Z_{st}, V_{st}, \beta, \delta)],$$

where wt(s,n) is the probability that a household with demographic characteristics A_{sn} is in household s's Zip Code.

The pairs of A_{sn} and wt(s,n) for n=1,2,…,N(s) is the distribution of the vector of demographic characteristics for household m's Zip Code taken from the American Community Survey.

Note that integrate joint distribution billing cycle-level consumption values with respect to density of A (unobserved vector of demographic characteristics) to account for persistence in household's demand

Functional Forms

$$\ln(w^*(p_w, V(A), A, Z, V, \beta)) = A'\beta_1 + Z'\beta_2 + \alpha(A,V)\ln(p_w) + \rho(V)\ln(V(A)) + \beta_7 V$$

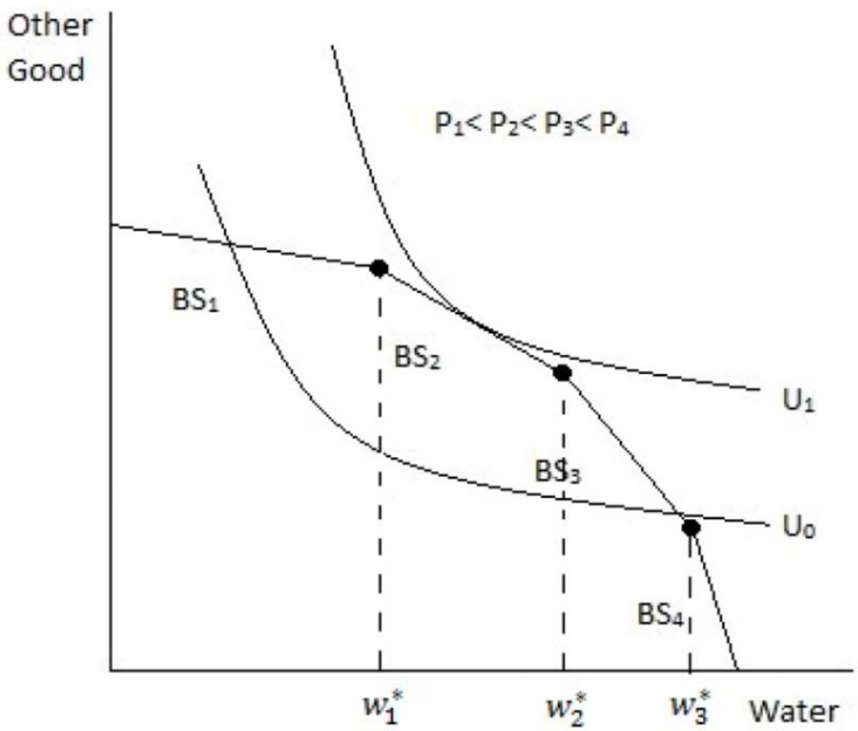
where $\alpha(A) = -\exp(A'\beta_3 + V\beta_4)$, and $\rho(V) = \exp(\beta_5 + V\beta_6)$
$\beta = (\beta_1', \beta_2', \beta_3, \beta_4')'$ as the vector of parameters of the demand function.

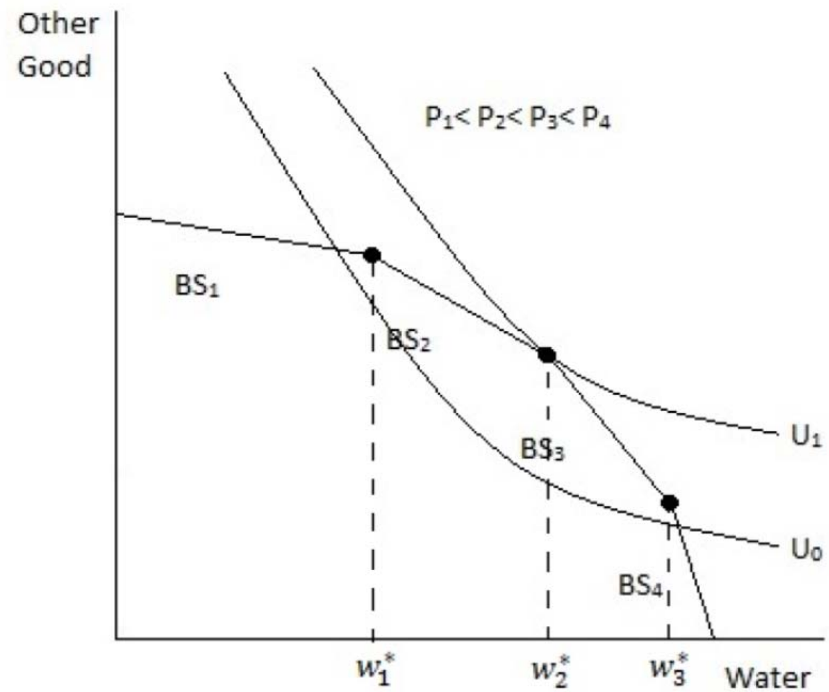
V(A) is the household's monthly virtual income and it is written as a function of this vector of demographic characteristics, because the household's income, M(A), is one of the elements of A.

The variable p_w is the marginal price of water for the step on the increasing block price schedule that the household is consuming at.

$\eta \sim N(0, \sigma_\eta^2)$ is observed by households and $\nu \sim N(0, \sigma_\nu^2)$ are unobserved by households. This implies that $\delta = (\sigma_\eta^2, \sigma_\nu^2)'$ in the notation of likelihood function.

Consumer Demand with Nonlinear Prices





Note slope of budget line = - P(water)/P(other goods)

Econometric Model/Likelihood Function Intuition

Consumers demand water services, which translates into uncertain gallons of water consumption

1) Minutes of shower, number of dishes cleaned, number of plants in garden watered, etc.

2) Different from labor supply decision with nonlinear budget set

Therefore, it is impossible to consume precisely X gallons of water for almost all uses of water services during the month

The distinction between water services demand and water consumption is modeled as follows

1) Choice given η is "monthly water services consumption" shown in previous figures

2) Realized water consumption, w, depends realized "water use uncertainty associated water service" for each water service incident in month and this is captured by value of v

Parameters of model estimated using Maximum Likelihood (ML)

Likelihood Function Derivation

The mapping from the realized values of the unobservables (η, ν) to the observed value of the logarithm of the household's monthly billing cycle-level consumption, ln(w), for a K-step increasing block price schedule takes the form

$\ln(w) = \ln(w^*(p_1, V_1(A), A, Z, V, \beta)) + \eta + \nu$

  if $\eta < \ln(w_1^*) - \ln(w^*(p_1, V_1(A), A, Z, V, \beta))$

$\ln(w) = \ln(w_1^*) + \nu$

  if $\ln(w_1^*) - \ln(w^*(p_1, V_1(A), A, Z, V, \beta)) < \eta < \ln(w_1^*) - \ln(w^*(p_2, V_2(A), A, Z, V, \beta))$

$\ln(w) = \ln(w^*(p_2, V_2(A), A, Z, \beta)) + \eta + \nu$

  if $\ln(w_1^*) - \ln(w^*(p_2, V_2(A), A, Z, V, \beta)) < \eta < \ln(w_2^*) - \ln(w^*(p_2, V_2(A), A, Z, V, \beta))$

$\ln(w) = \ln(w_2^*) + \nu$

  if $\ln(w_2^*) - \ln(w^*(p_2, V_2(A), A, Z, V, \beta)) < \eta < \ln(w_3^*) - \ln(w^*(p_2, V_2(A), A, Z, V, \beta))$

$\ln(w) = \ln(w_{K-1}^*) + \nu$

if $\ln(w_{K-1}^*) - \ln(w^*(p_{K-1}, V_{K-1}(A), A, Z, V, \beta)) < \eta < \ln(w_{K-1}^*) - \ln(w^*(p_K, V_K(A), A, Z, V, \beta))$

$\ln(w) = \ln(w^*(p_K, V_K(A), A, Z, V, \beta)) + \eta + \nu$

  if $\ln(w_{K-1}^*) - \ln(w^*(p_K, V_K(A), A, Z, V, \beta)) < \eta$

where $V_k(A) = M(A) - d_k$ for k=1,2,…,K and M(A) is household's monthly income which is written as a function of A, the vector of household demographics, because the household's monthly income is one of the elements of A.

Likelihood Function Derivation

In terms of this notation, the likelihood function conditional of A, for single household and billing cycle pair is equal to:

$$\sum_{k=1}^{K} \frac{\phi(s_k)}{\sqrt{\sigma_\eta^2 + \sigma_\nu^2}} (\Phi(r_k) - \Phi(n_k)) + \sum_{k=1}^{K-1} \frac{\phi(u_k)}{\sigma_\nu^2} (\Phi(m_k) - \Phi(t_k))$$

where $t_k = [\ln(w_k^*) - \ln(w^*(p_k, V_k(A), A, Z, V, \beta))]/\sigma_\eta$,

$r_k = (t_k - \rho s_k)/\sqrt{1-\rho^2}$, $\rho = \frac{\sigma_\eta^2}{\sqrt{(\sigma_\eta^2)(\sigma_\eta^2+\sigma_\nu^2)}}$

$s_k = (\ln(w_{it}) - \ln(w^*(p_k, V_k(A), A, Z, V, \beta))/\sqrt{\sigma_\eta^2 + \sigma_\nu^2}$,

$n_k = (m_{k-1} - \rho s_k)/\sqrt{1-\rho^2}$

$m_k = (\ln(w_k^*) - \ln(w^*(p_{k+1}, V_{k+1}(A), A, Z, V, \beta))/\sigma_\eta$,

$u_k = (\ln(w_{it}) - \ln(w_k^*))/\sigma_\eta$.

The multiplying this likelihood for billing cycle t for observation i by this same likelihood for all T(i) months for household i yields the likelihood function for observation i.

Variable Descriptions

Weather Variables--For each customer-bill cycling pair, compute measure of weather in the customer's Zip Code for the specific billing cycle recorded in the water data set. The weather data comes from Wunderground.com

Average high temperature: For each day, there is a high temperature value reported in Wunderground.com. This variable is average of daily values for customer's billing cycle

Difference between the 75th percentile and 25th percentile of temperature: To measure fluctuations of the temperature throughout a billing cycle for a customer, this variable computes inter-quantile range of the daily high temperature values reported customer's billing cycle

Weather Variables (Continued)

Total precipitation in billing cycle: Total amount of rain during the billing cycle for the customer's Zip Code. Normalize this amount to a month to compare across billing cycles.

Difference between the 75th percentile and 25th percentile of precipitation: The total amount of rain noted above could have fallen in one day, or have been spread throughout the billing cycle. Inter-quantile range of the daily precipitation values reported for a specific billing cycle at a customer's Zip Code.

Demographics Characteristics --All come from the PUMS data set.

Monthly income of household: The monthly reported income of the household observed in the PUMS data set in 2012 dollars. (Annual number divided by 12)

Number of people over 18 years old in household

Number of people under 18 years old in a household

House Size Indictors--House acreage between 1 and 10 acres, **House acreage above 10 acres (Excluded category is less than 1 acre).**

Number of bedrooms in a house

Important Note: Only have distribution of the vector of demographic characteristics in each Zip Code (not actual values for each household).

Assigning Demographic Characteristics to Households

Can use model parameter estimates to compute posterior probability that each household s has vector of demographics A_{sn}

$$pr\ (A_{sn}|W) = \frac{wt(s,n)\prod_{t=1}^{T(s)} g(w_{st}\ |P_{st},\theta_{st},A_{sn},Z_{mt},\beta,\delta)}{\sum_{n=1}^{N(s)} wt(s,n)\prod_{t=1}^{T(s)} g(w_{st}\ |P_{st},\theta_{st},A_{sn},Z_{mt},\beta,\delta)},$$

Can then assign vector of demographics, A_{sn}, to each household based on highest demographic characteristics with highest value of $pr(A_{sn}|W)$.

Parameters estimates also make it possible to compute an estimate of the distribution of household's water consumption and monthly bill for any nonlinear price schedule.

Can compute expected value and variance of these magnitudes

Household-level Distribution of Sales and Revenues

("Known" Demographics)

For prospective price schedule, $\theta^p(w, A^*)$, a household with demographics A* has expected consumption and the variance in this consumption equal to:

$$E[w^*(P,\theta^p,M,A^*,V,\varepsilon,\beta)] = \int_{-\infty}^{\infty} w^*(P,\theta^p,M,A^*,V,s,\beta) f(s,\gamma) ds,$$

$$V[w^*(P,\theta^p,M,A^*,V,\varepsilon,\beta)] = \int_{-\infty}^{\infty} (w^*(P,\theta^p,M,A^*,V,\varepsilon,\beta) - E[w^*(P,\theta^p,M,A^*,V,\varepsilon,\beta)])^2 f(s,\gamma) ds.$$

Expectation and variances can be taken with respect distributions of ε given A* assigned by above rule.

Household-level Distribution of Sales and Revenues

("Known" Demographics)

The household assigned A* demographics has expected monthly water bill and the variance of its monthly water bill equal to:

(*)

$$E[R(\theta^p(w^*(P,\theta^p,M,A^*,\varepsilon, V, \beta)] = \int_{-\infty}^{\infty} R(\theta^p(w^*(P,\theta^p, M, A^*, V, s, \beta), A) f(s,\gamma) ds,$$

$$V[R(\theta^p(w^*(P,\theta^p,M,A^*,V, \varepsilon, \beta)] = \int_{-\infty}^{\infty} R(\theta^p(w^*(P,\theta^p, M, A^*, V, \varepsilon, \beta)) - E[R(\theta^p(w(P,\theta^p, M, A^*, V, \varepsilon, \beta))])^2 f(s,\gamma) ds.$$

Household-level Distribution of Sales and Revenues

(Distribution of Demographics Unknown in Customer's Zip Code)
Two distributions

1) Prior distribution of demographics—wt(s,n)
2) Posterior distribution given model estimates-- $pr(A_{sn}|W)$

Household m, assigned a distribution of demographics has expected monthly water bill and the variance in its month water bill equal to:

(**) $$E[R(\theta^p(w^*(P,\theta^p,M,A,V,\varepsilon,\beta)] =$$
$$\sum_{n=1}^{N(m)} \int_{-\infty}^{\infty} wt(m,n) R(\theta^p(w^*(P,\theta^p,M,A_{mn},V,s,\beta),A) f(s,\gamma)ds,$$

$$V[R(\theta^p(w^*(P,\theta^p,M,A,V,\varepsilon,\beta),A]=$$
$$\sum_{n=1}^{N(m)} \int_{-\infty}^{\infty} wt(m,n)(R(\theta^p(w^*(P,\theta^p,M,A_{mn},V,\varepsilon,\beta)) - E[R(\theta^p(w(P,\theta^p,M,A,V,\varepsilon,\beta)])^2 f(s,\gamma)ds.$$

Comparing the variance of household's water consumption and total revenues to utility given assigned A_{sn} (*) and variance with respect to distributions of ε and A (**) provides a measure of the value of demographic information to utility.

System-wide Distribution of Sales and Revenues

Suppose there are J types of customers, where customers of type j have vector of observed attributes, A_j, and C_j is the number of type j customers in the utility's service territory. This implies that the expected sales of water by the utility (summed across all customers) associated with rate schedule $\theta^p(w,A)$ is:

$$\text{Expected System-wide Water Sales} = \sum_{j=1}^{J} \mathrm{E}[w^*(\mathrm{P}, \theta^p, \mathrm{M}, A_j, \varepsilon, \mathrm{V}, \beta]C_j$$

$$\text{Variance in System-wide Water Sales} =$$

$$\sum_{j=1}^{J} \mathrm{Var}[w^*\left(\mathrm{P}, \theta^p, \mathrm{M}, A_j, \varepsilon, \mathrm{V}, \beta\right)]C_j.$$

Following the same procedure for system-wide revenues yields:

$$\text{Expected System-wide Revenues} =$$

$$\sum_{j=1}^{J} \mathrm{E}[\mathrm{R}(\theta^p(w^*\left(\mathrm{P}, \theta^p, \mathrm{M}, A_j, \varepsilon, \mathrm{V}, \beta\right), \mathrm{A}]C_j$$

$$\text{Variance in System-wide Revenues} =$$

$$\sum_{j=1}^{J} \mathrm{Var}[\mathrm{R}(\theta^p(w^*\left(\mathrm{P}, \theta^p, \mathrm{M}, A_j, \varepsilon, \mathrm{V}, \beta\right), \mathrm{A}]C_j.$$

System-wide Distribution of Sales and Revenues

Any other function of the distribution of system-wide sales and revenues can also be computed.

Water utility or regulatory body might be interested in the probability that system-wide sales or revenues exceed or fall below a pre-specified value for a prospective rate schedule.

This methodology can be used to compute that probability.

Comparing the variance of system-wide water consumption and revenues given assigned A_{sn} *and variance with respect to distributions of* ε *and* A *provides a measure of the value of demographic information to utility.*

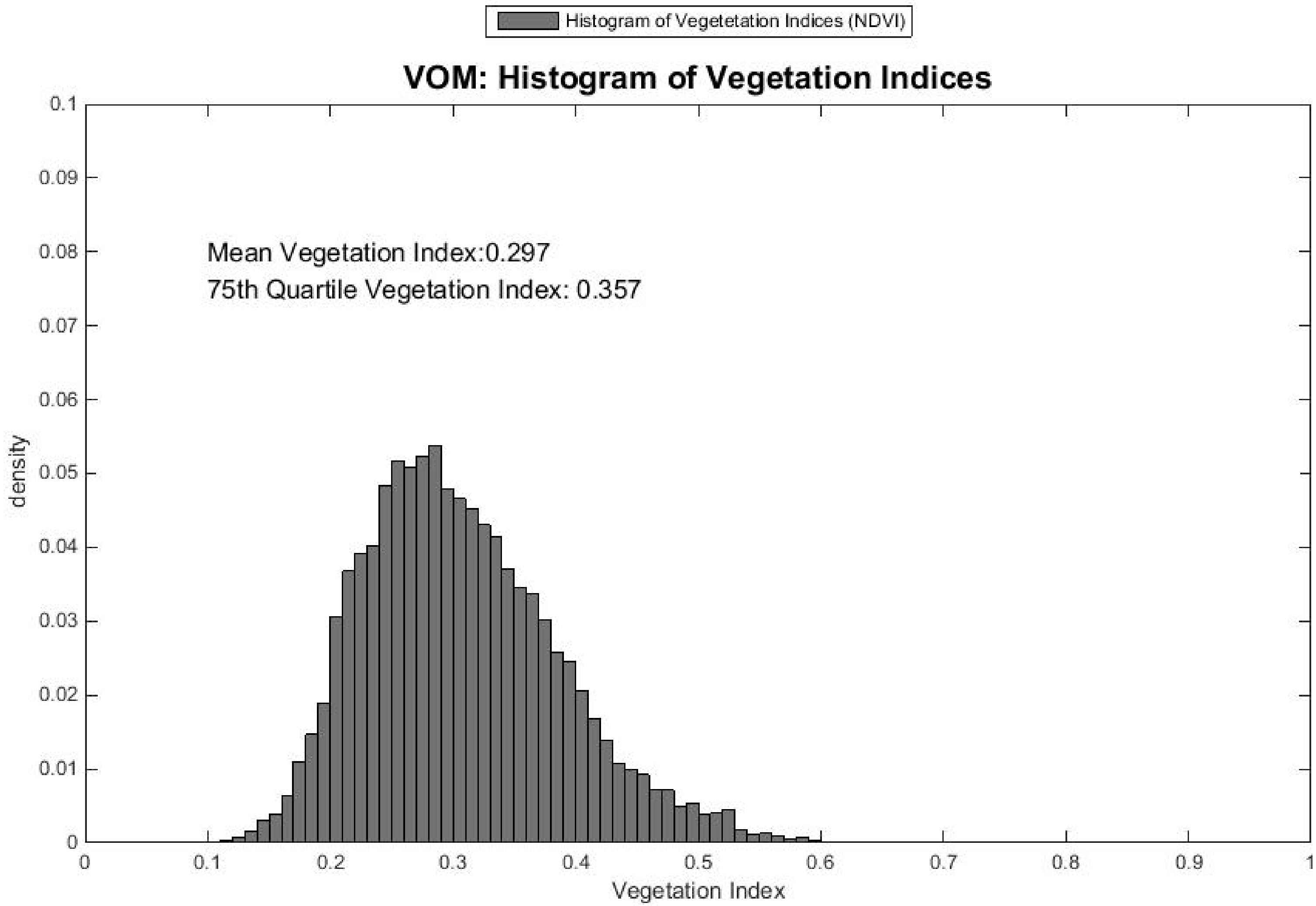
Table 1: Model Parameter Estimates and Standard Errors—Valley of The Moon, California

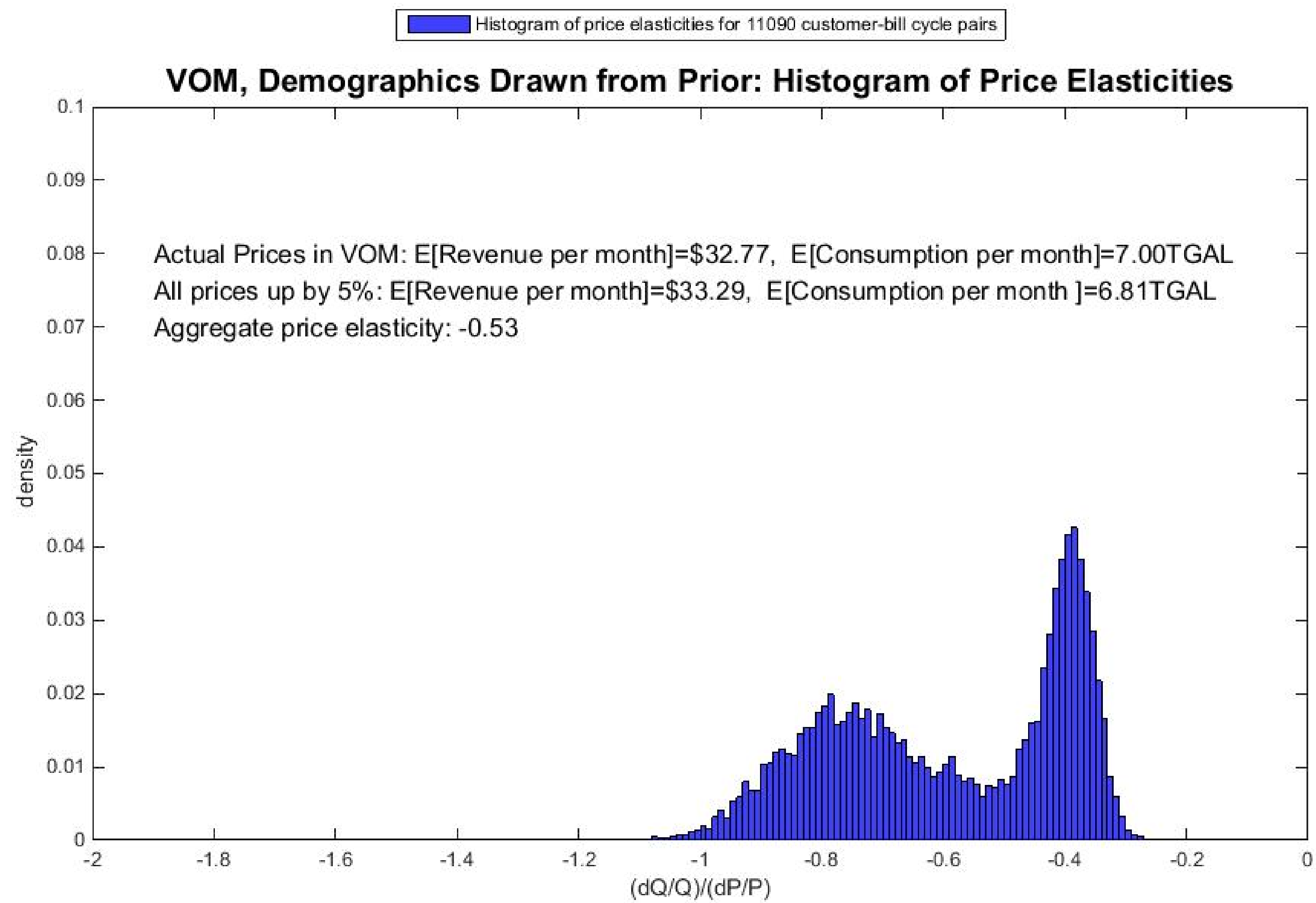
Parameter Name	Estimate	Standard Error (Outer Product of Gradients)	Standard Error (White (1982) Formula)
Constant in the income elasticity formula	-0.31125	0.01867	0.09857
Constant in the price elasticity formula	-0.83170	0.10444	0.31342
Std.dev. of household heterogeneity, η	0.27898	0.01190	0.08486
Std.dev. of optimization error, v	0.26800	0.01179	0.08305
Constant	-6.33831	0.38147	0.55999
Average high temp in billing cycle	0.00782	0.00169	0.00111
75th - 25th percentile of temperature in billing cycle	-0.01843	0.00203	0.00239
Total precipitation in billing cycle	0.00670	0.00459	0.00236
75th - 25th percentile of precipitation in billing cycle	-0.87861	0.37849	0.13993
Number of people over 18 in house	0.11379	0.02726	0.01570
Number of people under 18 in house	0.71123	0.02683	0.08927
House acreage above 1 acre	0.00088	0.03371	0.00106
Number of bedrooms in house	0.48981	0.07595	0.04090
Price*temp	-0.03615	0.00169	0.00862
Price*precip	0.00792	0.00222	0.00108
Price* # of adults	0.04054	0.03586	0.01603
Price* # of children	0.42252	0.02051	0.02822
Price* # of bedrooms	0.25201	0.01033	0.02526
Income* # of bedrooms	-0.02861	0.01493	0.00560
Vegetation Index	-0.15522	0.60903	0.00989
Income*Vegetation Index	0.02361	0.06266	0.00903
Price*Vegetation Index	0.05847	0.09878	0.00668

Number of customers 2001

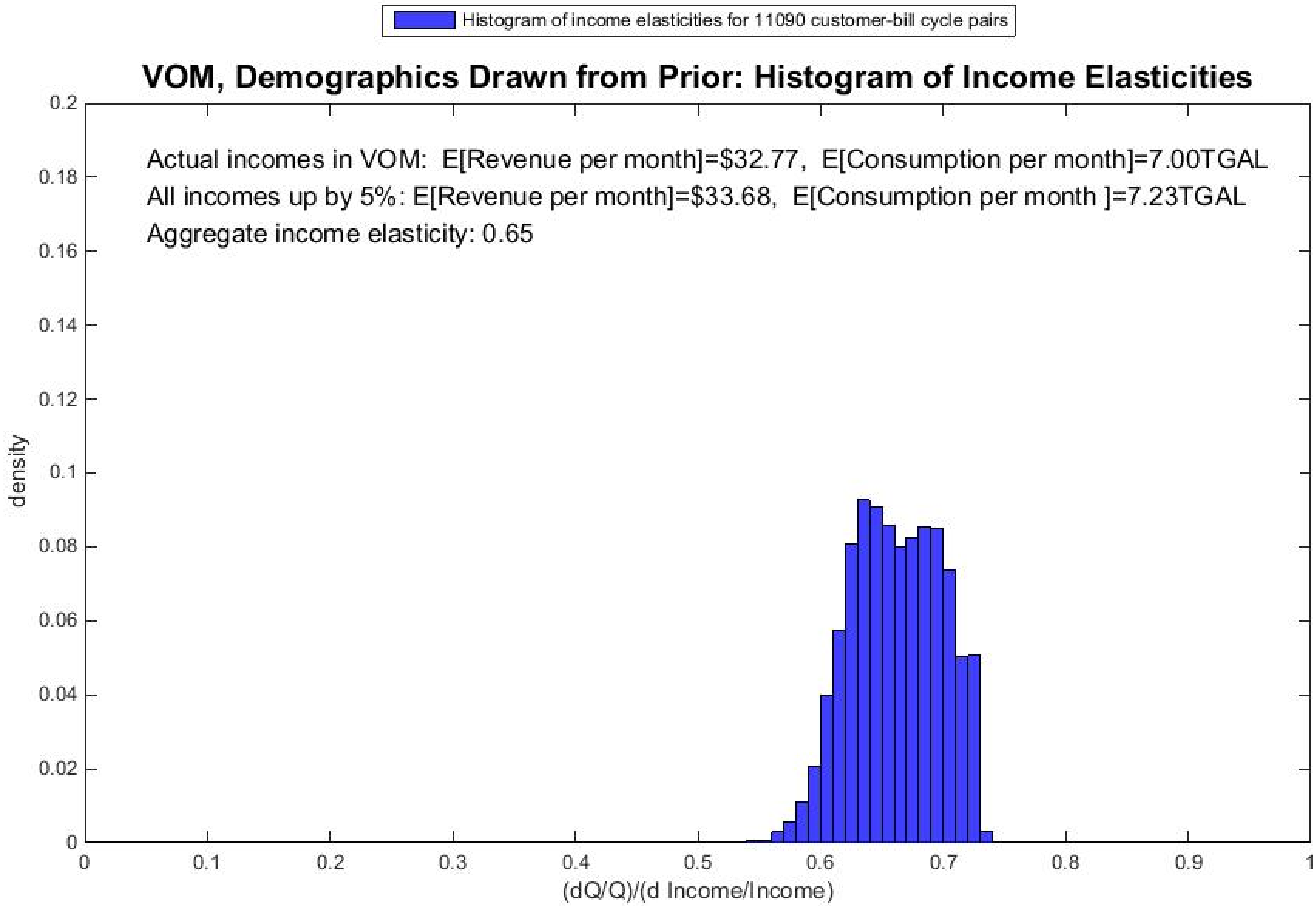
Price coeff. at mean of weather, demographic variables and veg. index: -0.44

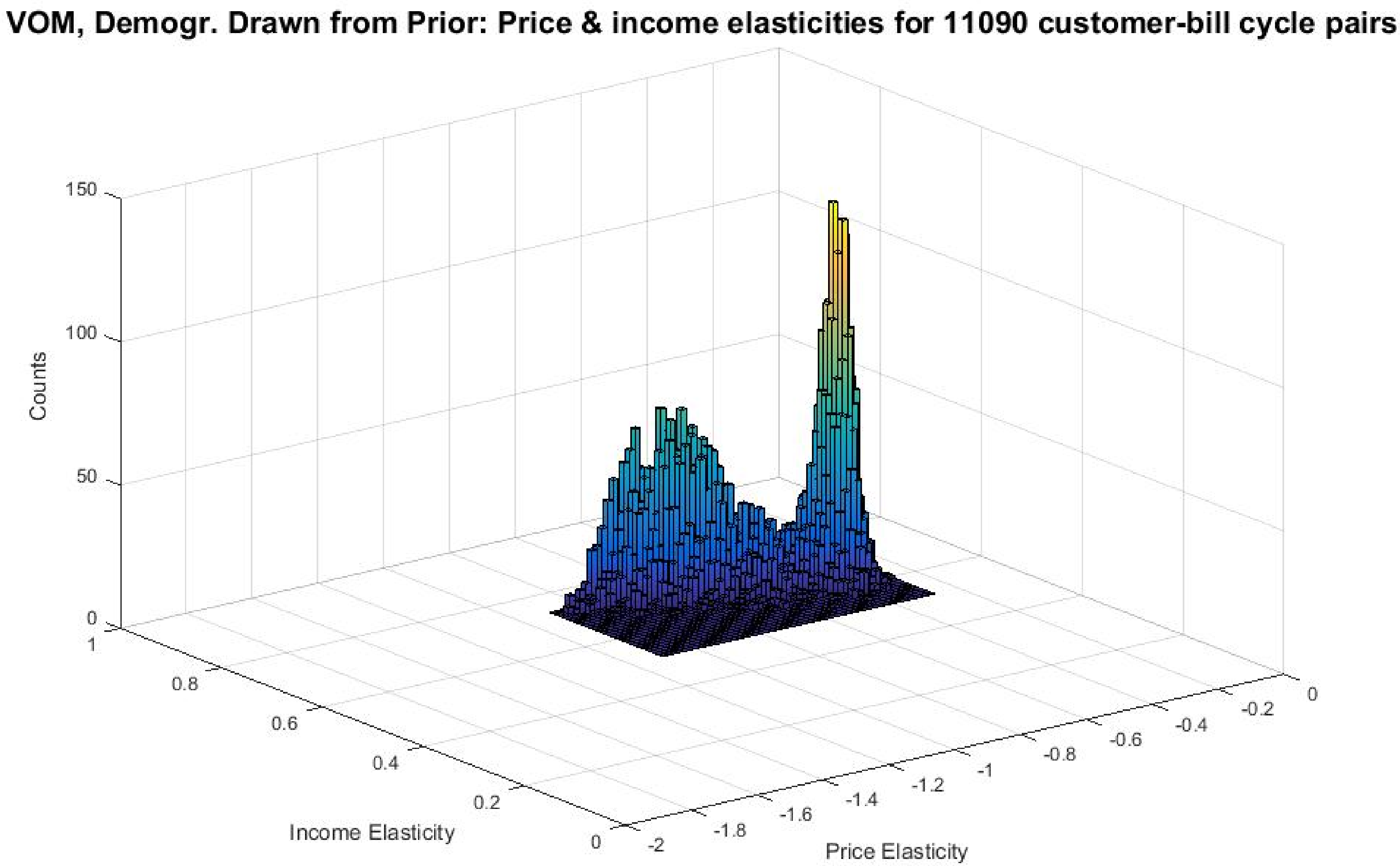
Income coefficient at mean of demographic variables and veg. index: 0.73


Histogram of Vegetetation Indices (NDVI)
VOM: Histogram of Vegetation Indices
Mean Vegetation Index:0.297
75th Quartile Vegetation Index: 0.357
density
Vegetation Index
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Histogram of price elasticities for 11090 customer-bill cycle pairs
VOM, Demographics Drawn from Prior: Histogram of Price Elasticities
Actual Prices in VOM: E[Revenue per month]=$32.77, E[Consumption per month]=7.00TGAL
All prices up by 5%: E[Revenue per month]=$33.29, E[Consumption per month]=6.81TGAL
Aggregate price elasticity: -0.53
density
(dQ/Q)/(dP/P)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0


Histogram of income elasticities for 11090 customer-bill cycle pairs
VOM, Demographics Drawn from Prior: Histogram of Income Elasticities
Actual incomes in VOM: E[Revenue per month]=$32.77, E[Consumption per month]=7.00TGAL
All incomes up by 5%: E[Revenue per month]=$33.68, E[Consumption per month]=7.23TGAL
Aggregate income elasticity: 0.65
density
(dQ/Q)/(d Income/Income)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

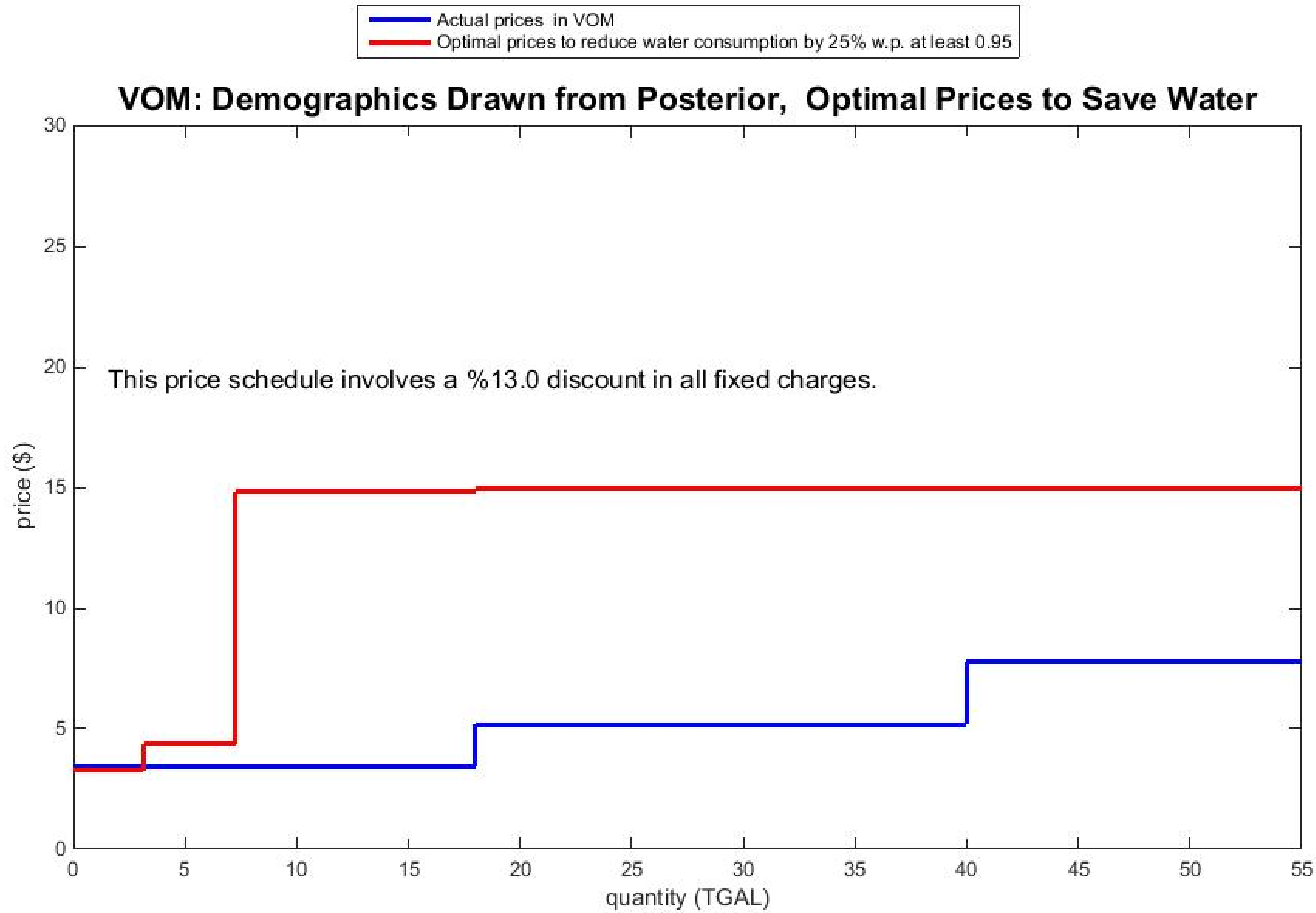

VOM, Demogr. Drawn from Prior: Price & income elasticities for 11090 customer-bill cycle pairs
Counts
150
100
50
0
1
0.8
0.6
0.4
0.2
0
Income Elasticity
-2
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Price Elasticity

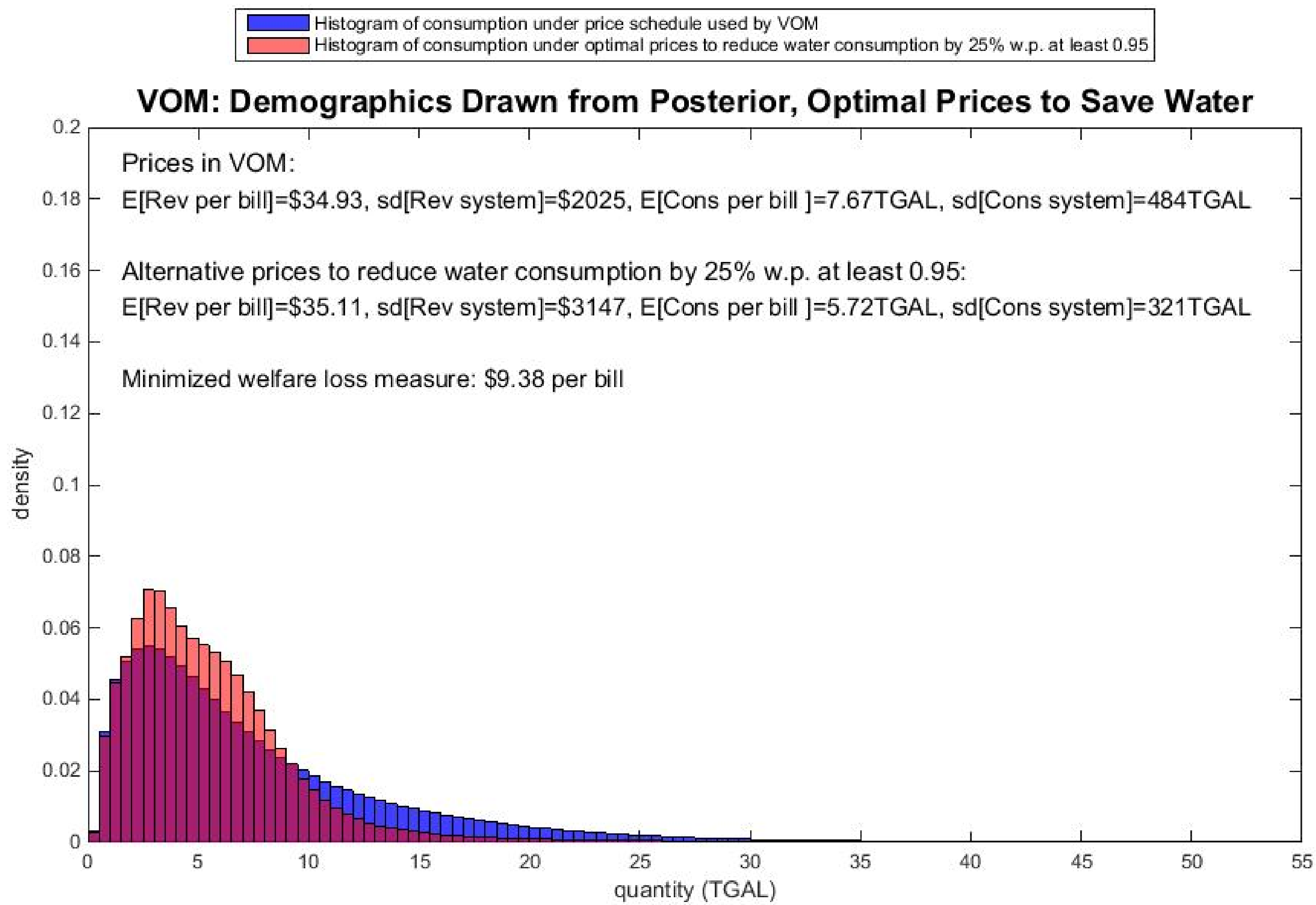
Rate Design Problem

Design rate schedule that minimizes weighted sum of squares of the differences between the expected revenue each household will have to pay under the new price schedule minus expected amount paid under the existing price schedule, subject to

1) Achieving a 25% reduction in water sales relative to last year with at least 95% probability
2) Recovering utility-wide expected revenue less than or equal to expected revenues under existing price schedule

Household's weight in objective function is inverse of expected revenue under current price schedule


Actual prices in VOM
Optimal prices to reduce water consumption by 25% w.p. at least 0.95
VOM: Demographics Drawn from Posterior, Optimal Prices to Save Water
This price schedule involves a %13.0 discount in all fixed charges.
price ($)
quantity (TGAL)
0
5
10
15
20
25
30
35
40
45
50
55



Histogram of consumption under price schedule used by VOM
Histogram of consumption under optimal prices to reduce water consumption by 25% w.p. at least 0.95
VOM: Demographics Drawn from Posterior, Optimal Prices to Save Water
Prices in VOM:
E[Rev per bill]=$34.93, sd[Rev system]=$2025, E[Cons per bill]=7.67TGAL, sd[Cons system]=484TGAL
Alternative prices to reduce water consumption by 25% w.p. at least 0.95:
E[Rev per bill]=$35.11, sd[Rev system]=$3147, E[Cons per bill]=5.72TGAL, sd[Cons system]=321TGAL
Minimized welfare loss measure: $9.38 per bill
density
quantity (TGAL)

Menu of Tariffs as a Way to Avoid Proposition 218 Protest

Two households with same monthly consumption, should have same cost, so one might argue that under Proposition 218 they should pay the same amount for water

By offering households a menu of tariffs and allowing them to choose

1) Two customers with same monthly consumption can pay different amounts for water, but each have the option to pay the same amount

2) Customers pay different amounts because they selected different tariffs from menu of tariffs offered

Solve same optimization problem as defined above subject to constraint that consumers face a menu of tariffs (two possible tariffs)

Consumers select tariff that maximizes their expected utility based on indirect utility function derived from estimates demand model under nonlinear pricing

Solution finds tariffs that separate households in two groups to achieve utility's pricing goal

Do Customers Respond to Nonlinear Prices?

Considerable controversy over the extent to which households correctly perceive nonlinear price schedules

Ito, K. (2014) "Do Consumers Respond to Marginal or Average Price? AER

Borenstein, S. (2009) "To What Electricity Price Do Consumers Respond? Residential Demand Elasticity Under Increasing-Block Pricing," UCEI

Propose alternative approach of specifying an explicit model of the demand with same functional form for utility and distributions of unobservables but households "respond" to different prices

Do Customers Respond to Nonlinear Prices?

Four alternate “price” models considered for same functional form for demand and distribution of unobservables

$$\ln(w^*(p_w, V(A), A, Z, V, \beta)) = A'\beta_1 + Z'\beta_2 + \alpha(A,V)\ln(p_w) + \rho(V)\ln(V(A)) + \beta_7 V$$

1) Actual price tier—p_w = tier price at their actual consumption
V(A) = actual income less the fixed connect charge
(Ignores utility-maximizing choice of price step)
2) Average variable price-- p_w = (Variable Cost of Bill)/(Actual Consumption)
V(A) = actual income less the fixed connect charge
3) Alternative actual price tier--—p_w = tier price at their actual consumption
V(A) = actual income less the fixed connect charge plus additional income due to nonlinear price schedule (Ignores utility-maximizing choice of price step)
4) Total Average Price--p_w = (Total Bill)/(Actual Consumption) and V(A) = actual income

Non-Nested Test of Nonlinear Price versus Alternative Price Models

All models give rise to log-likelihood $\ln(f(Y|X,\theta))$ and value of θ is estimated by maximum likelihood

Vuong (1989) proposed non-nested test between two competing parametric models for conditional density of Y given X

$$\text{H: } E(\ln(f(Y|X,\theta^*)) = E(\ln(g(Y|X,\gamma^*))$$
$$\text{versus K: } E(\ln(f(Y|X,\theta^*)) > E(\ln(g(Y|X,\gamma^*))$$

where E(.) is expectation with respect to true joint distribution of Y and X, θ^* and γ^* are plims of ML estimates of θ and γ.

Null hypothesis is expected value of log-likelihood of two models is equal versus alternative that under $f(Y|X,\theta)$ it is larger.

Implementing Non-Nested Hypothesis Tests

Estimate each of the four alternative models, $g(Y|X,\gamma)$ and compute $W_i = \ln(f(Y_i|X_i,\hat{\theta})) - \ln(g(Y_i|X_i,\hat{\gamma}))$, difference between maximized log-likehood value for ith observation for each model

Vuong (1989) shows that under null hypothesis

Z-statistic = $\sqrt{N}\bar{W}/S$ is asymptotically N(0,1) where

N = number of customers

$\bar{W} = \frac{1}{N}\sum_{i=1}^{N} W_i$

S = $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(W_i - \bar{W})^2}$

For all alternate price response models for both Cobb and VoM, null hypothesis is overwhelmingly rejected against alternative that nonlinear price model (presented earlier) has highest value average log-likelihood

Conclusions from Water Demand Modeling

No empirical evidence in favor of alternatives to nonlinear pricing model

Can design price schedules to achieve California's conservation goals with extremely high probability and not violate Proposition 218 requirements

Knowledge of customer-level heterogeneity in demographic characteristics and dwelling vegetation can significantly reduce revenue risk associated with achieving any water sales or revenue goal

- Standard deviation of utility-wide revenue declines from 85% to 95%
- Provides strong argument for utilities to "know their customers"
- Achieve any policy goal with less revenue or sales risk

Model can be used to achieve many other water pricing policy goals for utility

1) Limit bills to low income consumers for given utility-level expected revenue
2) Vegetation-index based pricing and other demographic characteristics-based pricing possible
3) Endogenize choice of vegetation index with vegetation-indexed based pricing

Concluding Comments

Growing support for wholesale water markets in policy-making community

1) *Underlines importance of a successful initial market design*
2) *A market that prices all relevant hydrological, environmental and legal constraints should maximize likelihood of success*

Water utilities must act more like Google, Amazon, and Facebook in terms of their knowledge of their customers

1) *Allows utilities to manage uncertain water availability with less revenue risk*
2) *Reduces need to engage in inefficient pricing mechanisms to make up for revenue shortfalls*
3) *Reduces incentives for inefficient operation*

Learn from other jurisdictions

Murray-Darling Basin Authority (MDBM) water market in Australia

Thank you for your attention.
Questions/Comments?