Journal of Water Resource and Protection, 2026, 18(7), 453-482
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

An Aggregate Household Water Demand Model for the Western United States

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How to cite this paper: Piper, S. (2026) An Aggregate Household Water Demand Model for the Western United States. *Journal of Water Resource and Protection*, **18**, 453-482.
https://doi.org/10.4236/jwarp.2026.187024

Received: June 12, 2026
Accepted: July 27, 2026
Published: July 30, 2026

Abstract

This paper presents the results of an aggregate water demand model using data from water suppliers in the 17 Western United States. The model uses data from readily available water use, price, water quality, climate, income and other socio-economic data. Household water demand models are estimated for the combined 17 western states and for individual states. The final water demand model includes the natural log of use per household per year as a function of the natural log of price, water quality, median household income, the annual average Palmer Drought Severity Index, household size, population density, percentage of population 65 and over, home ownership percentage, percentage of population with health insurance, and a state dummy variable. The price elasticity estimate for the 17-state model is −0.447 and state level elasticity estimates range from −0.114 in North Dakota to −0.775 in California. The aggregate model presented in this study is an improvement over previous studies because it is based on a large data set that covers a large geographic area. Greater variation in the magnitude of the explanatory variables included in the model supports robust econometric modeling and statistically significant results. The aggregate model can potentially be applied to a wide variety of areas in the western United States and can be used in a benefits transfer framework to estimate household water demand for areas within the western United States.

Keywords

Water Demand Modeling, Aggregate Household Demand Model, Western United States

1. Introduction

Past studies of household water demand fit into three categories: water demand modeling based on individual household data, meta-analysis using results from individual household water demand models to evaluate model characteristics that influence water demand modeling results, and aggregate demand models which use water use and price data at the water supplier level (e.g. municipality, suburb, water district, or private water service provider) to estimate aggregate household water demand functions. With the exception of meta-analysis studies, previous studies have generally used data from specific cities or small geographic regions utilizing surveys of individual households or accessing individual household data provided by water suppliers.

Aggregate water demand modeling using data from publicly accessible sources over a large region is an approach that can be used to reduce the difficulty in obtaining the data needed to estimate a water demand model and also provides data that has the variation in water use, price, and socio-economic conditions needed to estimate a robust model. Collecting data from many water service areas allows the impact of different water service area characteristics to be accounted for in the model. The results from this type of analysis can be applied to a specific area in a benefit transfer context to assess the value of water supply improvements or the cost of potential losses from rejected improvements.

This paper estimates an aggregate water demand model which can be applied to specific water supply study sites using existing readily available water use, price, water quality, climatic, income and other socio-economic data. Water use and price data for model estimation are obtained from existing surveys of water use and rates administered by state and local entities or are obtained directly from individual water supplier data. In some cases, county level United States Geological Survey (USGS) per capita domestic water use data are obtained at the county level and applied to water supply service areas within the county. Water quality data are obtained from the Environmental Working Group (EWG) Tap Water Database and climatic conditions are represented by the Palmer Drought Severity Index (PDSI) obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information. Socio-economic data are obtained from the U.S. Census.

The primary demand model estimated in this analysis represents the 17-state region of the Western United States. Additional models are estimated for 12 individual states that have sufficient observations for statistically significant results. The individual state results provide a basis for directly comparing the magnitude of the explanatory variables in the models. The estimated demand models represent the willingness to pay of water users for water service at the aggregate level and provide a basis for estimating domestic water supply benefits. The estimated demand models can also be used to project future water demand resulting from changes in price, water quality, climate, and socio-economic conditions. The results can be used to provide input and justification for potential improvements or expansion of water supply project benefits or to estimate changes in demand from changes in water rates. A water demand model provides a technique that is more rigorous and theoretically correct than simply using the price paid for water as a measure of value.

2. Literature Review of Water Demand Studies

Most previously completed household water demand studies have used individual water user data as the basis for model estimation or have used a hedonic approach based on city or county individual property value data to evaluate the impact of water supply characteristics on property values. Examples of these types of individual household studies include Alzahrani and Collins [1]; Barakat & Chamberlin, Inc. [2]; Griffin and Mjelde [3]; Hensher, Shore, and Train [4]; Howe *et al.* [5]; Koss and Khawaja [6]; and Renwick and Archibald [7]. The individual demand models require detailed water use, water price, or property data that is very time consuming to obtain and may not be readily available at the necessary level of detail. The individual models are very site specific and may be difficult to apply to other sites where demand estimates are needed.

Meta-analysis is based on using individual study results as individual observations and evaluating factors that significantly influence the variable of interest estimated in the study. Examples of water demand meta-analyses include Dalhuisen, *et al.* [8]; Espey, Espey, and Shaw [9]; and Sebri [10]. Meta analysis modeling is based on study estimates from around the United States and is therefore wider in scope than individual household data analysis. However, meta-analysis is more concerned with the influence of the types of models and the variables used on site-specific modeling results.

Previous research that is most relevant to this analysis are studies using the aggregated demand approach, which is also the least common type of approach. Five different studies were found and evaluated in terms of five characteristics:

- Type of model estimated;
- Explanatory variables included in the model;
- Number of observations;
- Geographic extent of the data used in the model;
- General results.

Moncur [11] estimated an aggregated water demand equation for single family households in Honolulu, Hawaii using ordinary least squares modeling. Pooled time series and cross-sectional data over 12 years were used resulting in 95 aggregated bimonthly observations. Explanatory variables for the demand model included the quantity of water consumed by a household in the previous time period, the price charged for water, household income, current monthly amount of rainfall in the area where the household lives, household size, and a dummy variable for water use restrictions. Despite the small number of observations, statistically significant results were obtained. The short run price elasticity of water was estimated to be −0.265 and the long run price elasticity was estimated to be −0.345, indicating inelastic demand (increase in price results in a relatively small decrease in the quantity of water used).

An aggregated model of 20 San Diego County Water Authority member agencies over 180 months (3600 observations) was estimated using a geographic fixed effects panel model [12]. This is essentially an ordinary least squares model with dummy variables assigned for geographic cross-sections. The variables used to estimate variation in water demand included season, temperature, precipitation, macroeconomic index, severity of water supply shortage restrictions, real marginal price, household size, housing density, median household income, and cross-sectional dummy variables. The estimated price elasticities for the San Diego County Water Authority model were −0.2321 for single-family homes and −0.1241 for multi-family homes.

Schneider and Whitlatch [13] used aggregated data for 16 communities in Columbus, Ohio and its suburbs over an 18-year period to estimate models of water demand. Water demand price elasticities were estimated for six user categories: residential, commercial, industrial, government, school, and total metered water users. The number of observations for each sector range from 108 industrial observations to 198 residential observations. A generalized least-squares procedure was used to estimate the model due primarily to autocorrelation issues common when using panel data. The variables used to explain variation in water use included price, per capita income, resident population per user account, single-family homes as a percentage of total homes, and summer precipitation which includes May through August precipitation. Price was a significant model variable for all user categories except the industrial sector. The short run price elasticity of demand was estimated to range from −0.112 to −0.438 and the long run price elasticity of demand was estimated to range from −0.262 to −0.956.

A study by Piper [14] evaluated the potential impact of changes in water quality in regions throughout the United States on water use and water supply benefits. The analysis included simultaneous estimation of water cost and water use models to represent the supply and demand relationships within the water market. To avoid potential simultaneity bias associated with price and quantity being endogenously determined, three stage least squares was used to estimate the supply and demand models. The source of water use, water price, water quality, system size, water source, and financial information was the 1996 American Water Works Association (AWWA) survey of water utilities across the United States. There were 309 utilities across 45 states in the AWWA database which the variables needed to estimate the supply and demand models. Variables in the water use model included household water use, water price, income, number of people per household, cost-of-living index for a region, water quality in terms of hardness, average annual temperature in a region, and average annual precipitation in a region. The average price elasticity of demand was estimated to be −0.32 with a range of about −0.10 to −0.80 depending on region.

Hoffmann, Worthington and Higgs [15] used suburb-level quarterly data from 1998 to 2003 to model suburb-level residential water demand in Brisbane, Australia. The average quantity of water consumed per household per quarter in each suburb is specified as the dependent variable in their regression. The explanatory variables included average household income, average household size, number of rainy days, number of warm days, and a summer quarter dummy variable. The model is estimated using ordinary least squares for both linear and non-linear (log-log) functional forms. The authors indicated the log-log specification was preferred due to a higher coefficient of determination (r-squared) and the short-run price elasticity of demand was estimated to be −0.507.

The literature review shows that a variety of modeling and econometric approaches have been used to evaluate household water demand. Individual household models use site specific data representing small areas and typically have a relatively small number of observations. Meta-analysis and aggregate demand studies have used straight-forward ordinary least squares approaches or modified approaches such as weighed least squares that do not require the level of sophisticated modeling techniques needed individual water use data models. Meta-analysis studies use information from a wide geographic area while most existing aggregate water demand studies rely on site specific data. The literature review indicates that there is a need to model water demand using data from a wide geographic area, with a large number of observations using model variables that support good statistical results and applicability to other areas.

3. Modeling Methodology

Estimating household water service demand models is complicated by three issues: 1) uncertainty regarding the relevant price that influences water use; 2) the timing of water bills reflecting the price water users react to, and; 3) difficulty in obtaining water use, price, and socio-economic data needed to estimate a water demand model.

Economic theory indicates marginal price is the relevant price affecting use. However, it is likely that water users do not accurately assess their marginal price at the time of use. Water bills typically provide total water use and total water cost information from which average and total cost is easily determined. Generally, water bills also provide information on rates by water use tier or category. Rate structure information can be used by a water user to estimate their marginal cost. However, water customers are not likely to complete this calculation and would be more likely to react to easier to understand average or total costs on their water bill. In addition, many water bills are paid through an automatic bill-pay process where few households look at marginal rates, and average or total cost is most relevant and would be noticed as a debt to their bank account. The price water customers react to is likely to be the most clearly presented information in a water bill, which is average cost or total water bill rather than the marginal price. Therefore, using average cost for the price variable seems reasonable.

Several studies have indicated using average price as the price signal for modeling utility demand may be preferred to marginal price because it may better capture consumer behavior when households do not perfectly understand complex, tiered rate structures. Santos and Guidetti [16] indicated households facing non-linear pricing structures for water and sewer service respond to average price rather than marginal price for two reasons: 1) they found no evidence of consumption bunching at kinks in price where marginal prices increase and, 2) they observed consumption changes in response to price adjustments that affected average price without altering the marginal rate. Brent and Ward [17] and Wichman [18] found that consumers do not respond to the marginal price of water because they do not fully understand marginal price, but they do understand average price and total water cost. Finally, Ito [19] found electricity consumers did not respond to marginal price, no kink in demand where marginal price changes, but they do respond to average price.

The cost (price) paid by household water customers may not be known at the time they are "purchasing" water for use, but the cost (price) of water from previous billing periods are known. The resulting delayed price signal means either a lagged price variable or a representative longer-term price is most relevant. Using average quarterly or annual water price over a period of time lends itself well to the aggregate modeling approach used in this study.

The use of average price does not remove endogeneity issues when modeling water demand using individual household data. The level of simultaneity bias may be reduced somewhat using average price because average price is not as sensitive to changes in use as is marginal price.

Using average water cost, mean price/cost per unit over a year, instead of price/cost at a point-in-time reduces the risk of simultaneity bias. The average reflects a longer-term, smoothed price signal, which is less correlated with unobserved shocks that affect both price and demand. The annual average price is less likely to suffer from simultaneity bias than a point-in-time price.

In addition, the data used in this analysis is not individual household level data but aggregated utility level data which further reduces potential simultaneity bias. For a given utility there are many households that are experiencing a wide variety of average prices and use. Individually, they are experiencing feedback effects between use and price. Aggregating individual price and quantity combinations and estimating the average of the average prices and use removes the direct feedback effect experienced by each individual. Each utility data point represents a single observation in the model. Average prices and average use at the water utility level reduces potential endogeneity bias of the model.

The aggregate water demand approach is similar to the use of aggregated data to estimate a zonal travel cost model (ZTCM) in recreation economics, where recreation participants are grouped into zones around a recreation site and a demand curve is derived by estimating the statistical relationship between aggregate trips from a specified zone and the average distance from that zone (the price proxy) to the site [20].

Within-zone variation in socioeconomic characteristics and quantities is not taken into account and statistically significant modeling results are less likely with an aggregated model compared to an individual model. As a result, coefficient estimates for the explanatory variables in an aggregate demand model are likely to be less precise than estimates for model variables using individual data. However, an aggregated data model still retains the basic demand relationship that is expected in theory, such as the negative influence of price increases on quantity used and a positive influence of income on the quantity used.

Data at the aggregate level for water service providers are generally publicly available from state, county, water works and rural water associations, the United States Geological Survey, the United Department of Commerce, the Bureau of Labor Statistics, the Environmental Working Group Tap Water Database, and the National Oceanic and Atmospheric Administration (NOAA). These data are not provided at the individual household level due to disclosure issues. Therefore, data at the aggregate level are much easier to obtain for modeling purposes.

The aggregate modeling approach in this analysis represents a general household water demand model using data from 17 states in the western United States. The model captures the essential factors that influence household water use as indicated by previous studies identified in the literature review. These factors include the price of water, climate, water quality, income, household size, and other relevant socio-economic variables. Data are gathered for 1330 water suppliers throughout the 17 western United States. Variation in average water use across water suppliers resulting from variation in average price is the basis for the demand curve estimation.

An important advantage of the aggregated data approach is that the model can be estimated using ordinary least squares rather than more complicated modeling such as two-stage least squares. An aggregate model does not have the problem of simultaneity bias (price and quantity being determined simultaneously) that an individual model has because average use is representative of all water users in the service area so there is no individual use feedback. Cordell and Bergstrom [21] indicate use of an aggregated model in the context of a ZTCM can be estimated using simple ordinary least squares because the aggregated models implicitly adjust for both the probability and frequency of participation in recreation. This same logic applies to the aggregated water demand model because the aggregated model adjusts for the household decision to use water for various purposes and the level of household water use for each purpose. As discussed above in the literature review in Section 2, ordinary least squares has been used in previous analyses of aggregate water demand.

4. The Aggregate Household Water Demand Model

The model developed in this analysis is an aggregate demand/consumption functions for water use by service area households. The conceptual model is shown below:

Water use per household per year = f(cost of water per gallon, water contaminants listed by the Environmental Working Group for a utility, median household income, annual average Palmer Drought Severity Index, household size, population density, percentage of population 65 and over, home ownership percentage, percentage of population with health Insurance, state dummy variable).

Initially, a cost-of-living index was included in the model as an indicator of the financial resources available to pay water bills, where a higher cost-of-living leads to reduced disposable income available for water payments. However, the cost-of-living variable may not be appropriate as a separate measure of financial resources for two primary reasons. First, median household income is already included as a variable representing financial resources. Including both cost-of-living and median household income is likely to create a multicollinearity problem. Second, the cost-of-living index includes the cost of utilities, so cost-of living would be collinear with the cost of water to some extent. The percentage of population in poverty was also initially considered for inclusion in the model to account for severe economic hardship. However, poverty percentage is closely related to income level, likely causing multicollinearity in the model.

To test the relationship between median household income, cost-of-living index, and poverty percentage, three regression models were completed for these income related measures. The three estimated models were:

Median Household Income = f(Cost-of-Living, Poverty Percentage);

Cost-of-Living = f(Median Household Income, Poverty Percentage);

Poverty Percentage = f(Cost-of-Living, Median Household Income).

The regression results showed that the explanatory variables in all three models were statistically significant, indicating a significant relationship between the three variables and the potential for multicollinearity if all three variables were included in the model.

Brief definitions and the expected signs for each variable included in the model are shown in Table 1.

Table 1. Variables and expected signs in the household water demand model.

Variable	Variable Defined	Expected Sign
Annual per household water use	Gallons used per household per year. The provider may be a municipality, water district, or other entity that provides water service.	NA (Dependent variable)
Cost/price per gallon	The average price paid by an average household	Negative
Environmental Working Group (EWG) contaminants	Number of contaminants in tap water	Negative
Median household income	Median household income in supplier area	Positive
Annual average Palmer Drought Severity Index (PDSI)	Indicator of drought conditions	Negative
Household size	Average number of people in the household	Positive
Population density	Number of people per square made in service area	Negative
Percentage of population 65 and over	Population 65 years of age or higher	Uncertain
Home ownership percentage	Percentage of household who own their home	Positive
Percentage of population with health Insurance	Percentage of population covered by health insurance	Uncertain
State dummy variable	Variable indicating which western state the water service area is located. Dummy variables are included for all states except Kansas.	Uncertain, varies by state

The price per gallon of water is represented by the average cost of water service for average use for each water supplier and the cost of that quantity of water. This average cost includes all costs paid by the water user for the representative quantity used by a household, in most cases average use.

The number of contaminants identified by the Environmental Working Group (EWG) that are detected after treatment is used as a proxy for water quality. A contaminant is counted for a water system if it exceeds EWG health guidelines over an approximate eight-year period of time (2013 to 2020). This variable is a proxy because not all water quality issues are noticeable, have the same level of impact on health and safety, and have an impact on behavior. Some systems have data that do not begin until 2014 and some have data that extends only until 2019. The period of time included in the EWG data set is long enough to be representative of the number of contaminants for each system. The number of contaminants is a measure that can be compared consistently across all water systems. The EWG notes that they do not rely solely on federal standards, but rely on scientific evidence, legal standards and health advisories to define water quality goals that will protect public health. The EWG drinking water standards are listed on their website [22].

Median household income represents the financial resources available to households for purchasing all goods and services needed and wanted by a household. Median household income is obtained from the 2020 Census.

The annual average Palmer Drought Severity Index (PDSI) is a climatic variable that accounts for temperature and precipitation. The PDSI uses temperature and precipitation data to estimate relative dryness. The PDSI is a standardized index that potentially spans from −10 (dry) to +10 (wet). Maps from meteorological related operational agencies like the National Oceanographic and Atmospheric Administration (NOAA) typically show a range of −4 to +4, but more extreme values are possible. The PDSI is used in the M&I demand model as a proxy for drought, since it is based on temperature data and a physical water balance model. The PDSI captures drought effects through changes in potential evapotranspiration. The PDSI values used in this analysis represent the average 2020 monthly value for the entire year which represents the base data year. A negative PDSI indicates dry conditions, therefore a lower PDSI is expected to result in a higher quantity of water demanded.

Household size has a direct impact on the amount of water used by a household and is expected to have a positive impact on total use per household. Population density is a proxy for open space that might be available for public and private landscaping, the concentration of housing in a service area, and overall concentration of water users in the service area. A greater density may mean smaller yards and less open space, a negative impact on use.

Percentage of population 65 and over, home ownership percentage, percentage of population with health insurance: These variables represent population characteristics that could influence the amount of water consumed by a household, or demand shifters. An older population may have different water use habits (different health needs, hobbies, etc.) than a younger population. Home owners may feel more invested in their yards and gardens and may be more willing to invest in water saving devices. The percentage of population with insurance is likely to have an impact on financial resources available to purchase goods and services. The impact of these variables and home ownership on use is uncertain.

The state dummy variables are included in the model to reflect regional variation that is not easily observed and measured and are not captured by the other variables in the model. The state dummy variables represent characteristics associated with different states that lead to structural differences in water demand. These differences could include water related regulations, tax policies, cultural differences, and code requirements. Including state dummy variables addresses possible omitted variable bias. State dummy variables control for unobserved differences between states.

There are 16 state dummy variables included in the model for data from 17 states. One state dummy is excluded, Kansas in this case, to avoid the dummy variable trap of perfect collinearity if all states are represented by a dummy variable which leads to unreliable coefficient estimation. The base case where all dummies are equal to zero represents the condition for Kansas.

4.1. Data Sources

Water cost and use data were obtained from several publicly available sources for each state. One important criterion of this analysis is to use information that is readily available and accessible to an analyst that want to estimate demand in a specific location or for a specific change on conditions. The data sources are described in detail in Appendix A. The rule for inclusion of a specific supplier in the data set was simply that average price/cost and average use data were available from public data. Average cost/price data are limited for domestic water connections because many systems provide a representative cost for a given level of use (for example 5000 or 10,000 gallons per month) rather than an average water cost for a household. Actual average bill is needed to accurately estimate average price, which limits the available domestic water utility observations. The data used for this analysis represent water utilities for which price/cost information was found after an extensive search through water utility and state water agency web sites. These are shown in Appendix A. Other water utilities may have this information but were not found during the data search.

Several states implement surveys of water suppliers which include water rate and use information. These surveys provide complete and consistent cost and use data. For some states, United States Geological Survey (USGS) county level per capita domestic water use estimates were applied to water service providers in that county and individual water provider rates were applied for that level of use. Using the USGS water use estimates for some providers creates data compatibility issues and possible measurement bias for these observations. An early iteration of the water demand model included a dummy variable for water use observations based on USGS data, but the USGS dummy variable was not found to be statistically significant. Despite the insignificant USGS dummy variable, inconsistent water use source data is a potential source of error in the model.

Data for median household income, household size, population density, the percentage of population 65 and over, home ownership percentage, and the percentage of population with health Insurance are all obtained from the U.S. Census Bureau for 2020. The Palmer Drought Severity Index (PDSI) data are provided on a weekly basis by the NOAA National Centers for Environmental Information. The PDSI annual average was calculated by first using the weekly average for 2020 to calculate a monthly average, then taking the resulting monthly averages to estimate an annual average. The source of water quality data is the Environmental Working Group (EWG) Tap Water Database. The EWG relies on scientific evidence, legal standards and health advisories to define water quality goals that will protect public health and contaminants of concern. The number of EWG contaminants is looked up on the EWG website for each water supplier by state.

The 2020 U.S. Census Bureau data is the best available data for the socio-economic variables used in the model and the 2020 PDSI average annual average was used to match the U.S. Census data. Water price and use data generally represented 2019 levels and in some cases the 2020 level. It should be noted that 2020 Census data represent conditions as of April 2020. The error introduced by combining annual average 2019 data with 2020 Census data is likely to be small. The data used was the best publicly available data.

4.2. Descriptive Statistics

Average and median household water use and cost for water suppliers included in the data for each state and for all 17 western states are shown in Table 2. Only a portion of the communities in each state are included in the data, with the possible exception of Kansas. Therefore, the values in Table 2 are representative for that state only to the extent that the included communities are representative of the entire state. However, the overall state comparisons show potential magnitudes of difference in use and cost between states.

Table 2. Aggregate state level household water use and cost data.

State	Number of observations	Average household use in gallons per year	Average household use in gallons per year	Average cost per gallon	Median cost per gallon
Arizona	18	109,800	101,664	$0.00633	$0.00517
California	27	119,808	116,616	$0.00655	$0.00537
Colorado	36	113,016	111,912	$0.00731	$0.00640
Idaho	37	294,852	271,008	$0.00226	$0.00182
Kansas	498	120,228	102,804	$0.00537	$0.00475
Montana	93	120,252	120,540	$0.00424	$0.00400

Continued

Nebraska	34	91,884	95,076	$0.00368	$0.00336
Nevada	25	130,140	127,452	$0.00602	$0.00408
New Mexico	17	91,272	84,000	$0.00596	$0.00581
North Dakota	66	73,272	69,348	$0.00571	$0.00672
Oklahoma	37	76,152	74,592	$0.00652	$0.00636
Oregon	18	69,024	62,664	$0.00939	$0.00801
South Dakota	31	51,144	47,376	$0.00995	$0.00868
Texas	115	64,644	60,000	$0.00781	$0.00710
Utah	161	190,452	180,888	$0.00343	$0.00280
Washington	38	108,300	93,192	$0.00565	$0.00564
Wyoming	79	124,848	121,488	$0.00479	$0.00408
17 States	1330	121,668	104,580	$0.00559	$0.00487

Table 3. Mean values of explanatory variables by state.

State	Number of EWG contaminants	Median household income	Annual average PDSI	Household size	Population density (persons per square mile)	Population 65 of age and over	Home ownership percentage	Percentage with health insurance coverage
Arizona	9.06	$64,573	−0.377855	2.62	1892.3	18.82%	64.77%	90.24%
California	10.81	$50,479	−1.39945	3.11	3509.0	12.80%	48.11%	90.47%
Colorado	9.25	$63,555	−2.00199	2.49	1770.8	17.81%	67.39%	89.97%
Idaho	5.27	$53,426	−1.05372	2.77	2164.8	14.42%	67.49%	88.10%
Kansas	10.09	$50,256	1.829510	2.37	992.6	20.62%	74.33%	90.56%
Montana	7.41	$47,409	1.089955	2.22	1067.4	24.43%	70.24%	90.24%
Nebraska	10.00	$57,087	2.106022	2.47	1862.1	17.28%	64.86%	91.31%
Nevada	13.00	$63,488	−1.18906	2.58	2409.0	19.77%	60.51%	89.82%
New Mexico	10.47	$43,593	−1.81825	2.63	989.2	20.36%	65.49%	92.29%
North Dakota	8.88	$63,244	3.261372	2.24	769.1	20.63%	76.55%	92.37%
Oklahoma	11.62	$56,309	2.699769	2.68	1248.8	15.32%	89.75%	86.76%
Oregon	3.33	$61,024	−1.84688	2.71	2710.4	15.34%	68.66%	92.97%
South Dakota	3.48	$59,302	4.858175	2.62	1371.9	16.79%	64.40%	90.29%
Texas	10.92	$59,718	−0.27168	3.38	1105.7	16.18%	69.18%	82.35%
Utah	7.03	$71,599	−1.84578	3.10	1343.1	15.64%	79.07%	90.96%
Washington	11.29	$82,429	−0.78369	2.65	3435.4	14.47%	59.70%	93.59%
Wyoming	8.53	$64,956	0.694637	2.60	1110.9	15.75%	72.14%	86.05%
17 States	9.18	$57,426	0.744829	2.61	1319.5	18.61%	72.23%	89.69%

Table 2 indicates that there is a general negative relationship between water price and quantity of water used, as would be expected. There is a wide range in water use and price from state to state, which was also expected given the range of climatic conditions, water quality, and treatment requirements for various suppliers in the 17 western states. Average values for the explanatory variables considered in the 17 western state model are shown in Table 3 for each state and for the 17 states as a whole.

5. Results for the 17 Western State Model

After Regressions were run using STATA econometric software. There were 1330 observations in the model and mean annual household water use for the model observations was 121,668 gallons (0.373 acre-feet) per year. Initially a simple linear model was estimated where the variables were not transformed in any way. The adjusted r-squared was approximately 0.50 and the F-statistic was significant at the 1% level. The adjusted r-squared represents the percentage of variation in the dependent variable (household water use) around the mean that is explained by the independent variables in the regression equation. A value of zero indicates none of the variation is explained by the model while a value of 1 indicates all of the variation is explained by the model. The F-statistic is a measure of the significance of the overall model.

The adjusted r-squared is relatively good for a model based on cross-sectional aggregated data although a higher adjusted r-squared would be preferred. There are three primary problems that are common with OLS models using cross-sectional data which need to be evaluated for the initial model. These problems include heteroskedasticity, specification error, and multicollinearity.

5.1. Heteroskedasticity

Modeling using cross sectional data (data collected from multiple individuals at one point in time) frequently exhibits heteroskedasticity. Heteroskedasticity in OLS regression analysis refers to the occurrence of a systematic change in the spread of the modeled residuals over the range of values of the dependent variable. A residual value is the difference between an observed value for a dependent variable minus the predicted value of the dependent variable (household water use in this case). The existence of heteroscedasticity leads to coefficient estimates that are less precise and trustworthy than a model that does not have heteroskedastistic errors and results in estimated t-statistics that tend to over-state the significance of an explanatory variable.

Several methods can be used to detect heteroskedasticity. The most basic technique is to look at a plot of residuals versus fitted values. This comparison shows that as the quantity of household water use increases, the variation of the residuals increases. Two commonly used formal tests are the Breusch-Pagan test and White's test, both of which are Chi-Square tests. The calculated Chi-Square using the STATA Breusch-Pagan Cook-Weisberg test for heteroskedasticity is about 733 and the calculated Chi-Square for White's test is 642. Both tests reject the hypothesis of constant variance, indicating heteroskedasticity is likely.

5.2. Specification Error

The model was also tested for omitted variables and incorrect functional form using the Ramsey Regression Specification Error Test (RESET) in STATA. The Ramsey RESET test result was a calculated F value of approximately 107, rejecting the null hypothesis of no omitted variables and correct functional form. Therefore, the initial model could have specification issues.

5.3. Multicollinearity

If a model has multicollinearity, the regression coefficients are not biased, but the standard errors are inflated and the t-statistics are no longer reliable. Multicollinearity exists when two or more of the independent variables in an OLS model have a linear relationship. As discussed above, correlation between median household income, percentage of the population in poverty, and the cost-of-living index was expected so the model included only median household income as an indicator of financial resources. Variance Inflation Factors (VIF's) were calculated for the initial regression modeling run to test for multicollinearity concerns. VIF's measure the extent to which the variance of an explanatory variable is influenced by its interaction with other explanatory variables. The VIF calculations indicate possible moderate multicollinearity between median household income, annual average PDSI, the state dummy variables for Utah and Texas, and household size.

5.4. Addressing Heteroskedasticity

There are three common approaches that are used to address heteroskedasticity:

1. Transformation of the dependent variable—Transforming the dependent variable in a way that reduces the influence of extreme values and makes the residuals approximately homoscedastistic. A common transformation is to take the natural log of the dependent variable.
2. Redefine the dependent variable—One example is to use a rate for the dependent variable rather than an absolute raw value.
3. Use weighted regression—Where a weight is assigned to each data point based on the variance of its fitted value.

For this analysis potential specification error and heteroskedasticity were addressed by converting the household water use and the water price variables into natural logs. Several previous studies have used the natural log transformation of use and price for their water use models [23]; Lyman [24]; Nieswiadomy [25]; Puri and Maas [26]; and Renwick and Archibald [7]. This transformation also has the useful property of transforming the estimated coefficient for price into a constant own price elasticity. The assumption of constant own price elasticity, through the relevant range of water prices, is reasonable given that a large change in water price would likely be needed to affect elasticity. The Ramsey RESET test provides additional support for transforming the functional form of the model.

The new transformed model was re-evaluated for heteroskedasticity and specification error. The STATA Breusch-Pagan/Cook-Weisberg calculated Chi-Square test statistic is now 8.6 (compared to 733 previously) and the calculated Chi-Square for White's test is 451 (compared to 642.06 previously). Both tests still reject the null hypothesis of constant variance at the 1% level, but the test statistics are much lower than before. The results of the Breusch-Pagan and White tests indicate heteroskedasticity is still a potential problem but may be less severe than before.

5.5. Addressing Specification Error

The Ramsey RESET test for the revised model has a calculated F value of 3.6 (compared to 107 previously) which results in not rejecting the null hypothesis of no omitted variables and correct functional form at the 1% level. Therefore, the natural log transformation appears to have potentially addressed the specification error in the initial model.

5.6. Addressing Multicollinearity

The issue of potential multicollinearity needs to be weighed against possible specification error created by removing possible multicollinear explanatory variables. Specification error results in bias while multicollinearity does not. Therefore, the theoretical need to keep median household income, annual average PDSI, household size, and state dummy variables outweighs potential multicollinearity. The major multicollinearity issue associated with measures of income was addressed by excluding poverty percentage and cost-of-living variables from the model.

6. Final 17 State Modeling Results

The regression results for the household water use model using the natural log of use per household and the natural log of water price per gallon are shown in Table 4. The adjusted r-squared is about 0.63 for the transformed model, which is good for an aggregate model. It should be noted that the adjusted r-squared of the initial model and the transformed model are not directly comparable due to the reduced scale of the natural log of use. The water quality proxy and household size variables are not statistically significant at the 10% level or better. The statistical insignificance of these two theoretically relevant variables is an indication of possible specification error due to poor proxy variables. There is also the possibility of an omitted variable, such as preferences to practice water conservation or the importance of having traditional landscaping. However, it is very difficult to find variables that specifically account for these types of preferences. The population density variable may partially address the landscaping issue.

Robust standard errors are presented in Table 4 which correct the standard errors and resulting t-statistics of a model with potential heteroskedastistic residuals. The model variables that were significant at the 5% level or better include cost per gallon, annual average PDSI, percentage with health insurance, population density, home ownership percentage, the percentage with health insurance, and 10 of the state dummy variables (Idaho, Nebraska, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, and Wyoming). Variables that were significant at the 10% level included all of the variables significant at the 5% level plus median household income.

Table 4. Regression results correcting for heteroskedasticity and potential specification error.

Explanatory Variable	Estimated Coefficient	t-statistics based on robust standard errors	Significant at 5% level	Significant at 10% level
ln Cost per Gallon	−0.4473751	−22.46	YES	YES
EWG Contaminants	0.0012710	0.39	NO	NO
Median Household Income	0.00000118	1.76	NO	YES
Annual Average PDSI	−0.0215719	−2.91	YES	YES
Household Size	0.0240634	1.20	NO	NO
Population Density	−0.0000174	−1.99	YES	YES
Population 65 Years of Age and Over	−0.2753437	−2.09	YES	YES
Home Ownership Percentage	−0.2426910	−2.80	YES	YES
Percentage With Health Insurance	−0.4417166	−2.63	YES	YES
Arizona	−0.0717940	−1.57	NO	NO
California	−0.0410497	−0.62	NO	NO
Colorado	0.0039424	0.05	NO	NO
Idaho	0.4091225	5.69	YES	YES
Montana	0.0298632	1.06	NO	NO
Nebraska	−0.3722079	−6.12	YES	YES
Nevada	0.0669933	0.91	NO	NO
New Mexico	−0.2002945	−3.06	YES	YES
North Dakota	−0.1077532	−3.49	YES	YES
Oklahoma	−0.2493015	−4.12	YES	YES
Oregon	−0.3891844	−5.31	YES	YES
South Dakota	−0.5277195	−7.29	YES	YES
Texas	−0.5284200	−10.41	YES	YES
Utah	0.1404484	2.84	YES	YES
Washington	−0.0935184	−1.58	NO	NO
Wyoming	−0.0795821	−1.99	YES	YES
Constant	9.7514070	NA	NA	NA

Mean ln Use = 11.56543
Number of observations = 1330
Adjusted r-squared = 0.626
F-statistic = 96.55
Root Mean Square Error = 0.32011

Arizona, California, Colorado, Montana, Nevada, and Washington all had insignificant state dummy variables. This may be due, in part, to the relatively small number of observations for these states. There were 18 Arizona observations, 27 California observations, 36 Colorado observations, 93 Montana observations, 25 Nevada observations, and 38 Washington state observations. These states in total represent 17.8% of the total model observations. There was an average of 78 observations per state for all 17 western states and 52 observations per state excluding Kansas, which alone had 498 observations. All of the states with statistically insignificant state dummy variables except for Montana had significantly fewer observations than the average for all 17 states and all 16 states excluding Kansas. A statistically insignificant state dummy variable means that the state does not have differences in unobservable characteristics (not structurally different) compared to Kansas, which is the base case.

7. Sensitivity Analysis of the 17 State Model

The stability of the modeling results, primarily the price elasticity of demand estimate and overall goodness of fit, was evaluated by specifying and estimating five additional models. These models included the following specifications:

- Dropping the state dummy variables,
- Using regional dummy variables in place of the state dummy variables,
- Dropping statistically insignificant variables from the original model,
- A model including only the most basic theoretical variables and state dummy variables, and
- The original model excluding the Kansas data.

The states included in each region for the regional dummy variable model are shown in **Table 5**. The modelling results for the regional dummy variable model are shown in **Table 6** for comparison with the full model using state dummy variables.

Table 5. States included in each region.

Region	States Included
Northern Great Plains	North Dakota, South Dakota
Southern Great Plains	Nebraska, Kansas
Southwest	Arizona, New Mexico, Oklahoma, Texas
Rocky Mountains	Colorado, Montana, Utah, Wyoming
Pacific Northwest	Idaho, Oregon, Washington
Pacific Southwest	California, Nevada

The estimated price elasticity of demand for the regional dummy variable model is approximately 12.6% greater than for the state dummy variable model (−0.5039 compared to −0.4474), although both estimates are very inelastic. The adjusted r-squared of the regional dummy variable model is significantly lower

(0.5684) compared to the state dummy variable model (0.6265) indicating the state dummy variable model has a better goodness of fit than the regional dummy model which could explain the difference in the price elasticity estimates.

Table 6. Regression results for water demand model using regional dummy variables.

Explanatory Variable	Estimated Coefficient	t-statistics based on robust standard errors	Significant at 5% level	Significant at 10% level
ln Cost per Gallon	−0.5039161	−25.58	YES	YES
EWG Contaminants	0.0043175	1.35	NO	NO
Median Household Income	0.00000047	0.01	NO	NO
Annual Average PDSI	−0.0326831	−5.36	YES	YES
Household Size	0.0037423	0.19	NO	NO
Population Density	−0.0000229	−2.35	YES	YES
Population 65 Years of Age and Over	−0.4059689	−3.00	YES	YES
Home Ownership Percentage	0.0013571	0.02	NO	NO
Percentage With Health Insurance	−0.2309549	−1.35	NO	NO
Southwest	−0.4052577	−10.56	YES	YES
Northern Great Plains	−0.2065409	−5.09	YES	YES
Southern Great Plains	0.0649607	−2.37	YES	YES
Pacific Southwest	0.0067104	0.13	NO	NO
Pacific Northwest	0.0232167	0.46	NO	NO
Constant	9.2463830	NA	NA	NA
Mean ln Use = 11.56543 Number of observations = 1330 Adjusted r-squared = 0.573 F-statistic = 124.92 Root Mean Square Error = 0.34412				

The results for the model excluding the Kansas data are shown in Table 7. The price elasticity of demand for the model excluding Kansas is essentially the same as for the model that includes Kansas data (−0.4555 compared to −0.4474). This result indicates the full model provides a robust representation of water demand in the western United States.

Table 7. Regression results for water demand model excluding Kansas data and using Texas as the base case.

Explanatory Variable	Estimated Coefficient	t-statistics based on robust standard errors	Significant at 5% level	Significant at 10% level
ln Cost per Gallon	−0.4554528	−15.63	YES	YES
EWG Contaminants	0.0066604	1.89	NO	YES
Median Household Income	0.00000147	1.84	NO	YES
Annual Average PDSI	0.0069502	0.96	NO	NO

Continued

Household Size	−0.0058403	−0.28	NO	NO
Population Density	−0.0000241	−2.53	YES	YES
Population 65 Years of Age and Over	−0.3047045	−1.84	NO	YES
Home Ownership Percentage	−0.1488137	−1.30	NO	NO
Percentage With Health Insurance	−0.2267279	−1.18	NO	NO
Arizona	0.4359330	7.79	YES	YES
California	0.5298152	7.49	YES	YES
Colorado	0.5523763	7.24	YES	YES
Idaho	0.9590156	11.01	YES	YES
Montana	0.4859597	8.62	YES	YES
Nebraska	0.0510249	0.62	NO	NO
Nevada	0.5835664	6.77	YES	YES
New Mexico	0.3372302	4.77	YES	YES
North Dakota	0.2676007	4.79	YES	YES
Oklahoma	0.1414738	1.82	NO	YES
Oregon	0.1934217	2.46	NO	YES
South Dakota	−0.1420165	−1.64	NO	NO
Utah	0.6890517	11.65	YES	YES
Washington	0.4162843	5.74	YES	YES
Wyoming	0.3950129	6.89	YES	YES
Constant	8.9860190	NA	NA	NA

Mean ln Use = 11.54855
Number of observations = 832
Adjusted r-squared = 0.7013
F-statistic = 90.32
Root Mean Square Error = 0.31146

Finally, a summary of the results for all five of the additional models are shown in Table 8.

Table 8. Regression results for alternative water demand models.

Model	Estimated own price elasticity	Adjusted r-squared	F-statistic	Root Mean Square error
Original model with all explanatory variables	−0.4474	0.6265	90.18	0.32011
Model without state dummy variables	−0.5695	0.5197	160.79	0.36302
Model using regional dummy variables in place of state dummy variables	−0.5039	0.5684	126.02	0.34412
Model dropping statistically insignificant variables	−0.4483	0.6266	104.30	0.32007

Continued

Model including only cost, median household income, PDSI, population density, and state dummy variables	−0.4562	0.6168	107.96	0.32406
Original model with all explanatory variables, excluding Kansas data, and using Texas as the base condition	−0.4554	0.7013	82.29	0.31146

The summary modeling results shown in Table 8 indicate the state dummy variables add considerably to the goodness of fit of the aggregate demand model, as represented by the adjusted r-squared values, and that the price elasticity of demand estimates for models that account for regional variation are consistent across models.

8. Modeling Results—Individual State Models

The 17-state model specification including the Kansas observations, but excluding state or regional dummy variables, was used to estimate separate individual state models. The primary purpose for estimating these individual state models is to estimate individual state water cost elasticities. The modeling results are summarized in Table 9. The individual state modeling results for those states where the overall model or the price variable is not significant are not considered reliable for evaluating the impact of a price change on use and are not included in the results presented in Table 9.

Table 9. Individual state water demand regression results showing own price elasticities, statistical significance, adjusted r-squared values, and statistically significant variables.

State	Observations	Estimated own price elasticity	Adjusted r-squared	Variables that are statistically significant at 5% level in state model
Arizona	18	−0.423	0.879	Price, home ownership, health insurance
California	27	−0.775	0.809	Price, PDSI, home ownership
Colorado	36	−0.533	0.733	Price, PDSI, Health insurance
Idaho	37	−0.458	0.444	Price, population density
Kansas	498	−0.361	0.543	Price, PDSI, household size, population density, home ownership, health insurance
New Mexico	17	−0.659	0.602	Price, water quality, health insurance
North Dakota	66	−0.114	0.813	Price, water quality, household size
Oregon	18	−0.365	0.814	Price
South Dakota	31	−0.611	0.656	Price
Texas	115	−0.363	0.397	Price, water quality, household size, population 65 and over, health insurance
Utah	161	−0.545	0.419	Price, PDSI, home ownership, health insurance
Wyoming	79	−0.679	0.696	Price, population over 65

All statistically significant estimated elasticities are inelastic and negative as expected and within the range of previous water use elasticity estimates. The variety in outcomes are the result of varying conditions in the states and are also likely influenced by the number of observations available. The specific estimated variable coefficients that are statistically significant shown in **Table 5** vary considerably by state. The individual state model results provide a basis for comparing price elasticity of demand estimates between states and understanding differences in the impact of rate changes on water use.

The individual state modeling results are not as good as the 17 western state model in terms of the number of statistically significant variables and overall explanatory power of the models. This is expected because of the greater variation in the data across the states and the overall number of observations.

9. Summary—Contributions and Limitations of the Model

The aggregate model presented in this study is an improvement over previous studies because it is based on a large data set from publicly available sources that covers a large geographic area. The data set is cross-sectional, where each observation represents average water use and price paid for all water users served by a water utility within the 17 western states. The explanatory variables chosen for the model in this analysis were found to be significant in previous studies. Greater variation in the magnitude of the explanatory variables included in the model supports robust econometric modeling and statistically significant results. The aggregate model can potentially be applied to a wide variety of areas in the western United States and provides an aggregate estimate of the price elasticity of demand for water service throughout the western United States. Therefore, the estimated model can be used in a benefits transfer framework to estimate household water demand for areas within the western United States.

Price elasticity of demand estimates from water demand models are frequently used by water suppliers to evaluate the effect of changes in water rates on use. The 17 western state model price elasticity estimate is −0.447, which means water demand is price inelastic and a 1% increase in price would lead to a 0.447% reduction in use. Therefore, if a water supplier increases the price of water, the result will be an increase in water use-based revenues. The state level modelling estimates range from −0.114 in North Dakota to −0.775 in California.

The estimated aggregate price elasticity for the 17 western states is well within the range of elasticities of studies described in the literature review section of this report. This is an important result considering the use of the aggregated modeling methodology. The meta-analysis of water elasticities by Espey, Espey, and Shaw [9] found an average price elasticity of demand of −0.51 and approximately 90 percent of the elasticity estimates were between 0 and −0.75.

There are several important results from the aggregate demand model. First is the significance of the Palmer Drought Severity Index (PDSI) variable. The negative estimated coefficient combined with the fact that a negative PDSI corresponds with a drier climate means that as climate becomes drier, all other variables held constant, domestic water demand is expected to increase and the PDSI coefficient provides a basis for estimating this impact.

Another important result is the significance of the socio-economic variable coefficients, which provide a basis for forecasting future demand. Finally, changes in the provision of domestic water supplies will lead to a change in the quantity available and used by households which can be translated into a corresponding value from which benefits can be estimated using the benefit transfer approach.

Benefit transfer is a method used to estimate economic values of a resource or service by transferring information from previously completed studies to another location and/or context [27]. Benefit transfer is often used when it is too expensive to conduct a full benefit analysis and/or there is too little time available to conduct an original valuation study, yet a measure of benefits is needed. It is important to note that benefit transfers can only be as accurate as the initial study. An analysis by Kirchhoff, Colby, and LaFrance [28] concluded that transferring a benefit function better represents specific site characteristics than a simple point estimate of benefit.

The water quality variable was found to be statistically insignificant, which was unexpected. However, it is likely that the generalized proxy variable used for water quality is simply not detailed enough to fully capture water quality impacts. Further research is needed to find a better proxy for water quality.

Individual state models were estimated for those states with statistically significant results. The individual state results are potentially useful for policy purposes because of the wide variation in own price elasticity estimates. The estimated elasticities from the individual state models show differences in how water users respond to changes in water rates at the state level. This information could be useful to state regulatory agencies as well as to individual water utilities to understand the effects of rate changes on water demand, water supplier revenues, and household water expenditures and how those effects vary by state.

The 17 western state model can also be evaluated in terms of how state level water use predicted by the model compares to actual household water use. This comparison is shown in **Table 10**.

Water use predicted by the model consistently underestimates use, except for North Dakota. The North Dakota overestimation is most likely due to very low price elasticity of demand for North Dkota relative to other states as shown in **Table 5**. The differences between predicted and actual water use are likely due to the aggregated nature of the modeling data and estimates and omitted relevant variables that are difficult to identify and not easily obtained from readily available sources. More research is needed in this area. Despite the shortcomings of the model, the analysis provides a useful tool for evaluating the potential impact of changes in the explanatory variables on water use, including rate changes. This is useful information for water utility planning purposes. In addition, the model provides a tool that can be applied in a benefit transfer context to evaluate infrastructure and price changes that are under consideration by a water utility.

Table 10. Actual mean household water use by state versus predicted use.

State	Actual state average use	Predicted state average use	Difference between actual and predicted
Arizona	109,800	95,111	−13.4%
California	119,808	101,269	−15.5%
Colorado	113,016	99,192	−12.2%
Idaho	294,852	246,452	−16.4%
Kansas	120,228	101,219	−15.8%
Montana	120,252	116,509	−3.1%
Nebraska	91,884	84,122	−8.4%
Nevada	130,140	114,108	−12.3%
New Mexico	91,272	86,704	−5.0%
North Dakota	73,272	85,825	17.1%
Oklahoma	76,152	71,410	−6.2%
Oregon	69,024	57,827	−16.2%
South Dakota	51,144	44,073	−13.8%
Texas	64,644	58,099	−10.1%
Utah	190,452	159,296	−16.4%
Washington	108,300	99,502	−8.1%
Wyoming	124,848	106,783	−14.5%

There are several important limitations to the model related to the aggregate nature of the data and proxy variables for water quality and climate. First, the results of a model using aggregated average data for a group of individuals are less precise than for a model using individual data because within group variation is not accounted for in an aggregated model. Therefore, application of an aggregate model to specific sites is subject to error as shown in **Table 10**. However, an aggregate model can still be useful for evaluating relative differences in use under different socio-economic and environmental conditions. Second, the water quality variable used in this analysis was not statistically significant even though water quality is clearly an important factor influencing use. Clearly a better proxy for water quality characteristics influencing use at the utility level is needed.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Alzahrani, F. and Collins, A.R. (2022) Impact of Public Water Supply Unreliability on Residential Property Prices in Marion County, West Virginia. *Agricultural and Resource Economics Review*, **51**, 105-129. https://doi.org/10.1017/age.2021.24

[2] Barakat & Chamberlin, Inc. (1994) The Value of Water Supply Reliability: Results of a Contingent Valuation Survey of Residential Customers. California Urban Water Agencies.

[3] Griffin, R.C. and Mjelde, J.W. (2000) Valuing Water Supply Reliability. *American Journal of Agricultural Economics*, **82**, 414-426. https://doi.org/10.1111/0002-9092.00035

[4] Hensher, D., Shore, N. and Train, K. (2005) Households' Willingness to Pay for Water Service Attributes. *Environmental & Resource Economics*, **32**, 509-531. https://doi.org/10.1007/s10640-005-7686-7

[5] Howe, C.W., Smith, M.G., Bennett, L., Brendecke, C.M., Flack, J.E., Hamm, R.M., *et al*. (1994) The Value of Water Supply Reliability in Urban Water Systems. *Journal of Environmental Economics and Management*, **26**, 19-30. https://doi.org/10.1006/jeem.1994.1002

[6] Koss, P. and Khawaja, M.S. (2001) The Value of Water Supply Reliability in California: A Contingent Valuation Study. *Water Policy*, **3**, 165-174. https://doi.org/10.1016/s1366-7017(01)00005-8

[7] Renwick, M.E. and Archibald, S.O. (1998) Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? *Land Economics*, **74**, 343-359. https://doi.org/10.2307/3147117

[8] Dalhuisen, J.M., Florax, R.J.G.M., de Groot, H.L.F. and Nijkamp, P. (2003) Price and Income Elasticities of Residential Water Demand: A Meta-Analysis. *Land Economics*, **79**, 292-308. https://doi.org/10.2307/3146872

[9] Espey, M., Espey, J. and Shaw, W.D. (1997) Price Elasticity of Residential Demand for Water: A Meta-Analysis. *Water Resources Research*, **33**, 1369-1374. https://doi.org/10.1029/97wr00571

[10] Sebri, M. (2014) A Meta-Analysis of Residential Water Demand Studies. *Environment, Development and Sustainability*, **16**, 499-520. https://doi.org/10.1007/s10668-013-9490-9

[11] Moncur, J.E.T. (1989) Drought Episodes Management: The Role of Price. *JAWRA Journal of the American Water Resources Association*, **25**, 499-505. https://doi.org/10.1111/j.1752-1688.1989.tb03085.x

[12] San Diego County Water Authority (2021) Water Demand Forecast and Model Update 2020. Hazen and Sawyer.

[13] Schneider, M.L. and Whitlatch, E.E. (1991) User-Specific Water Demand Elasticities. *Journal of Water Resources Planning and Management*, **117**, 52-73. https://doi.org/10.1061/(asce)0733-9496(1991)117:1(52)

[14] Piper, S. (2003) Impact of Water Quality on Municipal Water Price and Residential Water Demand and Implications for Water Supply Benefits. *Water Resources Research*, **39**, 1-9. https://doi.org/10.1029/2002wr001592

[15] Hoffmann, M., Worthington, A. and Higgs, H. (2006) Urban Water Demand with Fixed Volumetric Charging in a Large Municipality: The Case of Brisbane, Australia. *Australian Journal of Agricultural and Resource Economics*, **50**, 347-359. https://doi.org/10.1111/j.1467-8489.2006.00339.x

[16] Santos, C.T.R.D. and Guidetti, B.M. (2025) Expansion of Piped Water and Sewer Networks: The Effects of Regulation. Inter-American Development Bank.

[17] Brent, D.A. and Ward, M.B. (2019) Price Perceptions in Water Demand. *Journal of Environmental Economics and Management*, **98**, Article 102266. https://doi.org/10.1016/j.jeem.2019.102266

[18] Wichman, C.J. (2014) Perceived Price in Residential Water Demand: Evidence from a Natural Experiment. *Journal of Economic Behavior & Organization*, **107**, 308-323. https://doi.org/10.1016/j.jebo.2014.02.017

[19] Ito, K. (2014) Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing. *American Economic Review*, **104**, 537-563. https://doi.org/10.1257/aer.104.2.537

[20] Ward, F.A. and Loomis, J.B. (1986) The Travel Cost Demand Model as an Environmental Policy Assessment Tool: A Review of Literature. *Western Journal of Agricultural Economics*, **11**, 64-178.

[21] Cordell, H.K. and Bergstrom, J.C. (1989) Theory and Techniques for Assessing the Demand and Supply of Outdoor Recreation in the United States. USDA Forest Service, Research Paper SE-275. Southeastern Forest Experiment Station.

[22] Environmental Working Group (2025) EWG Drinking Water Standards: No-Compromise Benchmarks to Fully Protect Public Health. https://www.ewg.org/sites/default/files/2021-11/EWG_TWDBStandards-Chart_11.2021_PP03.pdf

[23] Kenney, D.S., Goemans, C., Klein, R., Lowrey, J. and Reidy, K. (2008) Residential Water Demand Management: Lessons from Aurora, Colorado. *JAWRA Journal of the American Water Resources Association*, **44**, 192-207. https://doi.org/10.1111/j.1752-1688.2007.00147.x

[24] Lyman, R.A. (1992) Peak and Off-Peak Residential Water Demand. *Water Resources Research*, **28**, 2159-2167. https://doi.org/10.1029/92wr01082

[25] Nieswiadomy, M.L. (1992) Estimating Urban Residential Water Demand: Effects of Price Structure, Conservation, and Education. *Water Resources Research*, **28**, 609-615. https://doi.org/10.1029/91wr02852

[26] Puri, R. and Maas, A. (2020) Evaluating the Sensitivity of Residential Water Demand Estimation to Model Specification and Instrument Choices. *Water Resources Research*, **56**, e2019WR026156. https://doi.org/10.1029/2019wr026156

[27] King, D.M. and Mazzotta, M.J. (2024) Ecosystem Valuation Website. The U.S. Department of Agriculture, Natural Resources Conservation Service and National Oceanographic and Atmospheric Administration. https://www.ecosystemvaluation.org/

[28] Kirchhoff, S., Colby, B.G. and LaFrance, J.T. (1997) Evaluating the Performance of Benefit Transfer: An Empirical Inquiry. *Journal of Environmental Economics and Management*, **33**, 75-93. https://doi.org/10.1006/jeem.1996.0981

Appendix: Sources of Water Use and Cost Information by State

▪ **Arizona**

The average cost of water was calculated using the estimated average use and the Water Infrastructure Finance Authority of Arizona Water and Wastewater Rates Dashboard posted by the University of North Carolina School of Government Environmental Finance Center at the website https://dashboards.efc.sog.unc.edu/az. Sources of water use information by supplier are listed below:

- Eloy—City of Eloy Potable Water System Master Plan. February 2007, Website: https://www.eloyaz.gov/DocumentCenter/View/229/Water-System-Master-Study-PDF?bidId=.
- Chandler—Official Website of Chandler, Arizona. Website: https://www.chandleraz.gov/residents/water/water-conservation/education-and-resources/for-residents/average-daily-water-use.
- Gilbert—Alliance for Water Efficiency, Financing Sustainable Water. Website: https://allianceforwaterefficiency.org/wp-content/uploads/2017/06/FINAL_AWE_Gilbert_Avoided_Cost_Analysis.pdf.
- Glendale—PHXWATERSMART. 2021 Annual Water Quality Report, For Customers of the City of Phoenix-Hedgepeth Hills Water System. Website: https://www.phoenix.gov/content/dam/phoenix/waterservicessite/documents/glendalehedgepethwqr2021.pdf.
- Goodyear—In Focus, Goodyear's Water Future. June 2022. Website: https://issuu.com/cityofgoodyear/docs/infocus_-_issue_143_-_june_2022.
- Kingman—City of Kingman Drought Contingency Planning Project Drought Contingency Plan WaterSMART Drought Response Program: Drought Resiliency. Website: https://www.usbr.gov/drought/docs/2022/dcp/DRP-001_CityofKingman_508.pdf.
- Oro Valley—Oro Valley water utility welcome message from director. Website: https://www.orovalleyaz.gov/files/assets/public/v/1/documents/water-utility/water-conservation/waterwelcomeguide_final_1.pdf.
- Payson—Payson 2020 Water Quality, Consumer Confidence Report, Public Water System AZ04-04-032. Website: https://www.jwwater.net/wp-content/uploads/2021/06/2020-Town-of-Payson-CCR-updated.docx.pdf.
- Peoria—Sustainable Peoria Plan August 2022. Website: https://www.peoriaaz.gov/home/showpublisheddocument/4282/637968447838713140.
- Phoenix, Prescott, Pinal County, Tucson, and Santa Cruz County—2021 Report to the Water Commission, Activities of Calendar Year 2020. City of

Flagstaff Water Services Division, Water, Wastewater, Reuse and Stormwater. Annual Report. Website: https://www.flagstaff.az.gov/DocumentCenter/View/70113/Report-to-the-Water-Commission-2July2021.

- Surprise—Integrated Water Master Plan, June 2022. Website: https://content.civicplus.com/api/assets/f08c4e95-459e-48fb-94bd-1c5fdf78f037?cache=1800.
- Tempe—The State Press. Website: https://www.statepress.com/article/2020/11/spbiztech-tempe-water-use-and-conservation#:~:text=Braden%20Kay%2C%20the%20director%20of,per%20day%2C%E2%80%9D%20Kay%20said.

▪ **California**

Water cost data were obtained from the California Water Boards, State Water Resources Control Board, California Small Water Systems Rates Dashboard for Water Systems between 500 and 3300 Connections. Rates as of July 1, 2020. Posted by the University of North Carolina School of Government Environmental Finance Center at the website https://dashboards.efc.sog.unc.edu/ca.

Rate data were also obtained from the California State Water Resources Control Board, Drinking Water—Public Water Systems Rates Information, California Open Data Portal. Website: https://data.ca.gov/dataset/drinking-water-public-water-systems-rates-information.

Water data were obtained from the Pacific Institute, California Urban Water Use Data, website https://pacinst.org/gpcd/table/ as well as USGS data at website https://waterdata.usgs.gov/ca/nwis/wu.

▪ **Colorado**

Water usage and water cost information are both available for Colorado from the Colorado Department of Local Affairs.

Colorado Department of Local Affairs, Division of Local Government. "2020 Colorado Municipal & Special District Water & Wastewater Rate Survey Results." Website: https://assets1.cbsnewsstatic.com/i/cbslocal/wp-content/uploads/sites/15909806/2021/06/2020-Colorado-Water-and-Wastewater-Rate-Survey.pdf.

▪ **Idaho**

Water use was estimated using USGS per capita county averages and applying the average to the number of people per household.

▪ **Kansas**

Water usage and water cost information are both available for Kansas from the Kansas Department of Agriculture. The 2017 data is the most recent available and is indexed to 2020 prices.

Kansas—Kansas Department of Agriculture, Division of Water Resources. Municipal Water Use in Kansas, 2017. Report prepared in cooperation with the United States Geological Survey. Website:
https://www.agriculture.ks.gov/home/showpublisheddocument/1910/638445763374340000.

- **Montana**

Water usage and water cost information are available for Montana from a 2016 Montana Department of Natural Resources and Conservation statewide water and wastewater rate study. More recent 2019, 2021, and 2023 Montana Statewide Water and Wastewater Rate Studies were completed but the detail was not provided for each community from which water use and a consistent price per acre-foot could be derived. Therefore, the household use and price estimates are based on the 2016 rate study with prices indexed to 2020.

- **Nebraska**

Water use was estimated using USGS per capita county averages and applying the average to the number of people per household.

- **Nevada**

Water use was estimated using USGS per capita county averages and applying the average to the number of people per household.

- **New Mexico**

Average water use information was obtained from a Bureau of Reclamation Technical Report, City of Gallup Municipal and Industrial Water Supply Ability to Pay Analysis. The water use estimates in the report were obtained from the municipalities directly. The rates applied to the estimated use were obtained from the New Mexico Environment Department Water and Sewer Rate Surveys.

Bureau of Reclamation. City of Gallup Municipal and Industrial Water Supply Ability to Pay Analysis. Technical Report, Technical Service Center, Denver, Colorado. August 2011.

New Mexico Environment Department. Water and Sewer Rate Surveys. Website:
https://www.env.nm.gov/drinking_water/rates/.

- **North Dakota**

Water usage and water cost information are available for North Dakota from a 2019 North Dakota League of Cities water rate survey. North Dakota League of Cities, North Dakota 2019 City Water Rate Survey (Completed June 2019).

- **Oklahoma**

Water use was estimated using USGS per capita county averages and applying the average to the number of people per household.

▪ **Oregon**

Water usage and water cost information are available for some Oregon water suppliers from the League of Oregon Cities website. Water usage estimates were confirmed at the city websites.

League of Oregon Cities. Water Rates Data 2021, Website: https://data.orcities.org/City-Financial-Data/Water-Rates-Data-2021/ym9k-v6dn/data.

▪ **South Dakota**

Water use was estimated using USGS per capita county averages and applying the average to the number of people per household.

▪ **Texas**

Water usage and water cost information are both available for Texas from the Texas Municipal League. 2020 Texas data were used for the analysis.

Texas Municipal League. Water & Wastewater Survey, 2020 Results. Website: https://www.tml.org/229/Water-Wastewater-Survey-Results.

▪ **Utah**

Utah—Water usage and water cost information was obtained from a 2014 Utah Department of Natural Resources report. This report includes the most recent data available for Utah and is indexed to 2020 prices. It is assumed that the survey data are representative of conditions experienced in 2020. The report is Municipal and Industrial Water Supply and Use Studies, Utah State Summary 2014 Prepared by the Utah department of Natural Resources Division of Water Resources October 14, 2014. Website: https://water.utah.gov/wp-content/uploads/2019/03/2010-M_I-Statewide-SummaryCH.pdf.

▪ **Washington**

Water use information is obtained from the Washington State Department of Health Drinking Water System Data at website https://doh.wa.gov/data-statistical-reports/environmental-health/drinking-water-system-data.

Per capita water use information at the county level was also obtained from USGS Water Use Data for Washington at website https://waterdata.usgs.gov/wa/nwis/wu.

Water rate data were obtained from individual entities.

▪ **Wyoming**

Water usage and water cost information are available for Wyoming from a 2016 Wyoming Water Development Commission survey. Later surveys have been conducted but the level of detail was not sufficient to derive use and cost

estimates.

Wyoming Water Development Commission. "State of Wyoming 2016 Public Water System Survey Report." Website: https://wwdc.state.wy.us/watsys/2016/raterept.pdf.