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Modeling the Effects of Conservation, Demographics, Price, and Climate on Urban Water Demand in Los Angeles, California

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Abstract With a service area population exceeding four million people and with close to 90 % of the water supply being imported from sources outside the city, the Los Angeles water system is subject to multiple stressors, including climate change and population growth. The influence of various factors on water demand in Los Angeles was evaluated through development and application of multiple linear regression models for residential, commercial, industrial, and governmental water demand categories from 1970 to 2014 in the service area of the Los Angeles Department of Water and Power. Performance of the models in describing historical water demand was compared using the coefficient of determination, mean average percent error, and normalized root mean square error. Overall, the results of the linear regression models demonstrated that each water demand category is affected by different parameters. However, price and population were found to have the most significant impact on all categories. The seasonality of residential water demand was well described with the model based on monthly data, with precipitation and temperature being highly significant factors. Fitting of the residential data furthermore revealed that price and conservation have significantly counteracted the impact of population growth on water demand.

Keywords Urban water demand · Water management · Water conservation · Regression analysis

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1 Introduction

A key aspect in planning, design, operation, and sustainable management of a water system is the accurate prediction of water demand. Analyzing water demand is complex, as factors impacting demand are numerous and dynamic. Some of these factors, such as population growth and climate change, pose significant challenges to the sustainability of water supplies in cities (Dahal et al. 2016). The Los Angeles area is especially prone to drought and has very limited local water sources (Ashoori et al. 2015). Although the population growth of Los Angeles has slowed since the late 20th century, it is expected to expand in the future (LADWP 2015; Fuller and Harhay 2010). This increase in population and susceptibility to drought will place even greater pressure on the already limited amount of water in the region, and on the external sources of water that supply Los Angeles. Forecasts of water demand for Los Angeles must consider the range of complex factors influencing demand on all consumer categories, including residential, commercial, industrial, and governmental (LADWP 2015).

Reducing water demand to decrease stress placed on water supplies from climate change, population growth, and other factors has been investigated in previous studies. For example, Lettenmaier et al. (1999) showed that water demand had a greater impact on a water supply system compared to the effects of climate change on source water. In an analysis of effects of climate change on water withdrawal and supply through 2050, Roy et al. (2012) presented that water withdrawals in southern California would exceed 100 % of the available precipitation.

In this work, the focus was on modeling the water demand of each demand category in the Los Angeles water system to identify the dominant factors impacting each category. Sixty-six percent of the total water demand in Los Angeles is for residential consumers with the remaining 34 % coming from commercial consumers, government, and industrial accounts (LADWP 2015). Residential consumers consist of single-family dwellings, which are homes with only one family, and multi-family dwellings, which consist of households living in apartments. The differences between these dwellings were analyzed to evaluate the impact of outdoor water use and conservation on residential water demand in Los Angeles. Finally, yearly and monthly water demand models were developed and analyzed to assess the seasonal effects of precipitation and temperature on water demand.

1.1 Population

The U.S. Census Bureau projects that the population of Los Angeles will increase from its current value of 3.9 million in 2014 to 4.5 million by the year 2035. This will impact the demand for water, the supply of which is already under stress due to climate change and environmental restoration programs (Ashoori et al. 2015). Several studies have used regression analysis to understand the impact of population on water demand (Ruth et al. 2007; Mohamed and Al-Mualla 2010). Despite the increase in water demand that comes with growing population, as population in Los Angeles has increased over the past two decades the total demand for water has stayed approximately the same (LADWP 2015). Many factors have been shown to influence reductions in per capita water use, including water price, conservation efforts, and fluctuations in climate (e.g., Babel et al. 2007; Olmstead 2010).

1.2 Water Price

Previous studies have shown that people conserve water when it is priced at a higher level (Gaudin 2006; Rinaudo et al. 2012). Residents are responsive to price and it is important to know the impact of price elasticity, i.e., the change in demand related to a change in price. During periods of drought, increases in water prices in Los Angeles have induced lower demand for water through voluntary responses (Frederick 1997). Los Angeles restructured its water pricing in 1993 to integrate a tiered rate structure. After the drought years of 2007–2009, the tiered water price structure was modified. Customers were charged an increased (Tier 2) fee if they used more than the allocated Tier 1 water level. This rate structure is still in use in Los Angeles. The tiered water pricing structure gives consumers monetary incentives to be more efficient and to reduce water use (LADWP 2015).

1.3 Conservation Methods

Southern California's water conservation methods can be categorized as voluntary, mandatory, and market-based (Maggioni 2015). Market-based strategies are implemented through water pricing, and complement voluntary and mandatory strategies which rely upon regulation, information, and consumers' sense of community responsibility. These conservation methods, such as ordinances, rebate programs, and education of consumers regarding water stresses, have been implemented in Los Angeles since 1990. Voluntary conservation was introduced in 1990 whereas mandatory conservation started in 1991 after several years of drought in the 1980s (Ngo and Pataki 2008). The integration of water conservation incentives, education, and mandatory ordinances has had an effect on the reduction of water demand in Los Angeles and is therefore imperative to model.

1.4 Climate

Climatic variables, such as temperature and precipitation, have an effect on short-term seasonal changes in water demand, especially in arid areas such as Los Angeles. Single-family residents in Los Angeles use more than 50 % of their water for outdoors purposes, whereas multi-family households use closer to 30 % (LADWP 2015). That percentage fluctuates depending on the precipitation and temperature of the region. Increases in precipitation drive down water demand and increased temperatures raise overall water demand, e.g., in relation to water use for outdoor landscaping (Billings and Jones 2008; Jain et al. 2002). Climate variables thus need to be included in analysis of water demand in Los Angeles.

1.5 Demographics

Fluctuations in median household income have been shown to impact water demand (Harlan et al 2009). As median household income increases, the proportion of income used to pay for water decreases. Households with higher income thus experience a lower equivalent cost for their water, resulting in an increase in water demand. However, socioeconomic heterogeneity is difficult to be observed when median household income is averaged throughout Los Angeles. To understand the differences between socioeconomic groups within Los Angeles, single and multi-family households were compared. Studies have shown that lower income households are more likely to live in multi-family units compared to households who live in single-family dwellings (Santamouris et al. 2007). Single-family households with higher incomes are assumed to use more water due to outdoor landscaping, pools, and larger homes (House-Peters et al. 2011).

The overall objective of this study was to develop and evaluate models for water demand in Los Angeles to gain insight into factors that influence residential, commercial, industrial, and governmental demand. Various regression techniques, such as multiple linear, piecewise, and geographically weighted regression, are available for modeling water demand (House-Peters and Chang 2011; Wentz and Gober 2007). In this study, multiple linear regression (MLR) models of monthly and yearly water demand were developed and compared to evaluate their effectiveness. In order to evaluate the performance of the models, coefficients of determination (R^2), mean average percent error (MAPE), and normalized root mean square errors (NRMSE) were calculated. The novelty of this study lies in the identification of different drivers of water demand amongst each water use sector. The analysis of the MLR water demand models for each water demand category provides insights into the relative importance of factors affecting water demand and the sustainability of the future water supply in Los Angeles. Implementing these different models for evaluation of historical water demand data can also inform the selection of a model for use in predicting water demand in Los Angeles under various future scenarios of climate and population.

2 Methodology

2.1 Data Collection

The Los Angeles Department of Water and Power (LADWP) organizes its consumer classes into five categories: single-family household, multi-family households, commercial, industrial, and governmental. Single-family dwellings are houses with one family residing in the house whereas multi-family consists of apartments with two or more dwelling units served by one water meter. Single-family and multi-family dwellings comprise the total residential water demand in Los Angeles. The commercial demand category in Los Angeles consists of service-providing facilities and businesses, which can include restaurants, stores, universities, warehouses and storage facilities. The industrial category includes buildings or areas in use to produce goods. Finally, the governmental category consists of buildings owned and operated by the government, including public schools, parks, and other governmental buildings. In this study, water use by each consumer class was used as a dependent variable to understand the various factors that impact each of the demand categories (Table 1).

The MLR models were fitted to historical water demand data for Los Angeles. Yearly water demand data for each consumer class (single-family, multi-family, commercial, industrial, governmental) were available for the period from 1970 to 2014 from the Los Angeles Department of Water and Power (Fig. 1). Additionally, data for monthly residential water demand, which consists of single and multi-family households, were available for the same time period.

Independent variables considered in the analysis include climatic data, population, price of water, Los Angeles median household annual income and conservation level (Table 1). The variables in Table 1 were chosen as candidates for inclusion in the various models based on previous research on water demand (Babel et al. 2007; House-Peters and Chang 2011). Pricing was separated into two variables: Tier 1 and Tier 2. Prior to 1993, Los Angeles had no tiered water rates and there was one set price for water use. After 2009 tiered water prices were further adjusted, and differences in the tiered rates became more significant. Additionally, Tier 2 prices varied between consumer sectors, whereas Tier 1 prices stayed the same throughout all sectors. All price values for median household income and water prices were adjusted to 2012 prices.

Table 1 Dependent and independent variables in the MLR models of Los Angeles, California water demand

Dependent variables in the models	Units	Variable indicator	% distribution^
Total monthly residential demand	m^3 water	RD_M	(66)+
Total yearly residential demand	m^3 water	RD_Y	(66)+
Total yearly single-family demand	m^3 water	SFD	37
Total yearly multi-family demand	m^3 water	MFD	29
Total yearly commercial demand	m^3 water	CD	17
Total yearly industrial demand	m^3 water	ID	3
Total yearly governmental demand	m^3 water	GD	8
Independent Variables in the Models	**Units**	**Variable Indicator**	**Data source**
Total monthly precipitation	cm	R_M	NOAA
Total yearly precipitation	cm	R_Y	NOAA
Average monthly temperature	°C	T_M	NOAA
Average yearly temperature	°C	T_Y	NOAA
Tier 1 price	$/$m^3$ water	WP1	LADWP
Tier 2 price	$/$m^3$ water	WP2	LADWP
Total estimated monthly population	# people	P_M	LADWP
Total estimated yearly population	# people	P_Y	LADWP
Conservation level		C	LADWP
Low*		C_L	LADWP
Medium*		C_M	LADWP
High*		C_H	LADWP
LA annual median household income	$/month	MHI	U.S. Census Bureau

^ Non-revenue water, which is the difference between total water use and billed water use, accounts for 6 % of the total water demand for Los Angeles and was not included in the study

+ Accounts for the total amount of single and multi-family water demand

* Indicates categorical dummy variables. Each conservation level is individually compared to very low levels of conservation

A distinguishing feature of the present study is the inclusion of conservation as an explanatory variable in water demand modeling. The level of conservation was categorized into four groups (very low, low, medium, and high) dependent on the number of conservation initiatives implemented, as well as the estimated amounts of hardware and non-hardware conservation given by LADWP from 1970 to 2014 (Table 2). Specific implementation of conservation measures and estimates of hardware and non-hardware conservation can be observed in the Online Resource Tables A3 and A4. Conservation initiatives have included utility operations, public information programs, and incentives. After 1990, LADWP introduced further water conservation and water efficiency measures to reduce water demand. Three conservation levels (low, medium, high) were used as categorical dummy variables in the MLR models and were individually compared against a very low level of conservation. Distribution of the conservation level amounts was divided evenly among the three levels.

LADWP has relied on conservation as one of its main tools to increase water supply reliability. The LADWP Water Supply Action Plan, which was developed in 2008, sets plans to conserve water by more than 60 million m^3 per year by 2030 through hardware and non-

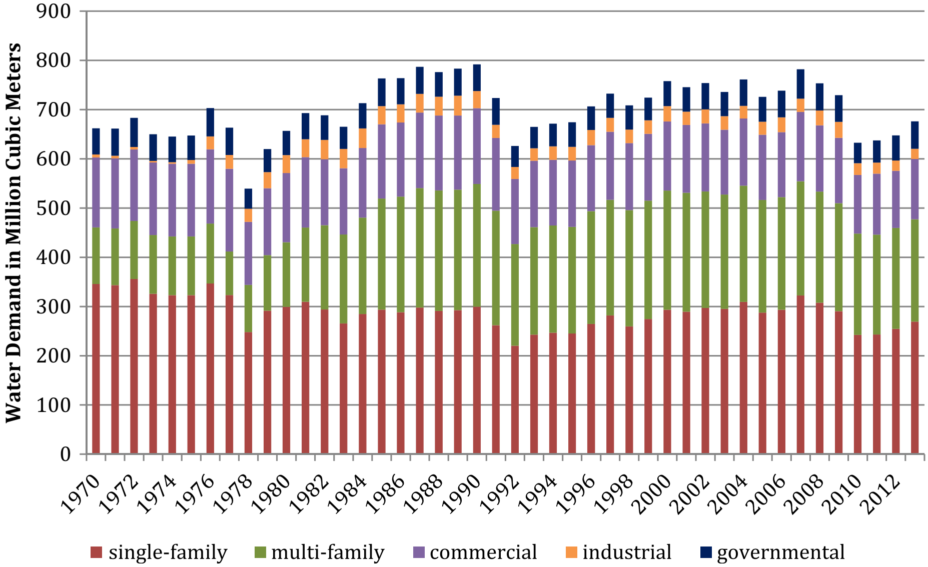

Fig. 1 Annual water demand per category in Los Angeles from 1970 to 2014

hardware methods (LADWP 2015). Hardware conservation programs have included high efficiency toilets, dishwashers, washing machines, and other water saving products. As a key part to maintaining the reliability of water supply, LADWP has placed into motion rebate programs that have incentivized people to switch to high-efficiency appliances. For example, in 2009 Los Angeles adopted the Water Efficiency Requirements Ordinance, which requires installation of high efficiency plumbing in new and renovating properties.

Non-hardware conservation is the estimate of water saved due to consumer behavior. For example, taking shorter showers and changing outdoor landscaping at a residence. Changes in consumer behavior and lifestyle have helped decrease the total water demand in Los Angeles, but the contribution of non-hardware conservation is difficult to quantify (Straus et al. 2016). Public outreach has included seminars on water conservation, education in schools, and public service announcements. Criteria for water conservation levels were developed to understand the overall impacts of conservation levels on each of the five consumer categories.

The potential to conserve water is highest in the commercial and industrial consumer categories (LADWP 2015). Residential water demand, conversely, has been steadily decreasing due to conservation efforts. By reducing overall water demand through conservation, the City of Los Angeles will rely less on imported water. The amount of water demand in Los

Table 2 Criteria for conservation levels in Los Angeles, California

Conservation level	Number of conservation measures	Estimated cubic meters of hardware and non-hardware water conserved (LADWP)	Value of conservation level if criteria is met
Very low	≤20	$\leq 3.60 \times 10^6$	C = 0
Low	21–30	3.61×10^6–1.50×10^7	$C_L = 1$; Else $C_L = 0$
Medium	31–40	1.51×10^7–2.60×10^7	$C_M = 1$; Else $C_M = 0$
High	40 <	2.60×10^7 <	$C_H = 1$; Else $C_H = 0$

Angeles is influenced by consumer investment in conservation, and modeling that relationship is imperative to future water planning management.

As indicated in Fig. 2a, the population of Los Angeles increased steadily throughout most of the study period from 1970 to 2014. However, the residential water demand exhibited yearly and decadal variations which differed from the strictly upward temporal trend of population. Following a predominantly increasing trend in the first half of the study period (until 1990), the residential water demand exhibited both periods of increase and decrease, with very little net change over the period 1990–2014 (Fig. 1). To what extent can this variable response of water use to population be explained by weather/climate variations and the demand influences of changing price and conservation efforts? Visual inspection of the dataset cannot provide a clear answer to this question. Instead formal methods are needed to identify and isolate the contributions of each factor. The multiple linear regression models described in the following sections were designed to accomplish this objective.

2.2 Multiple Linear Regression

Simple and multiple linear regression models have previously been applied in water demand modeling (Bougadis et al. 2005; Nieswiadomy 1992). The multiple linear regression models in this

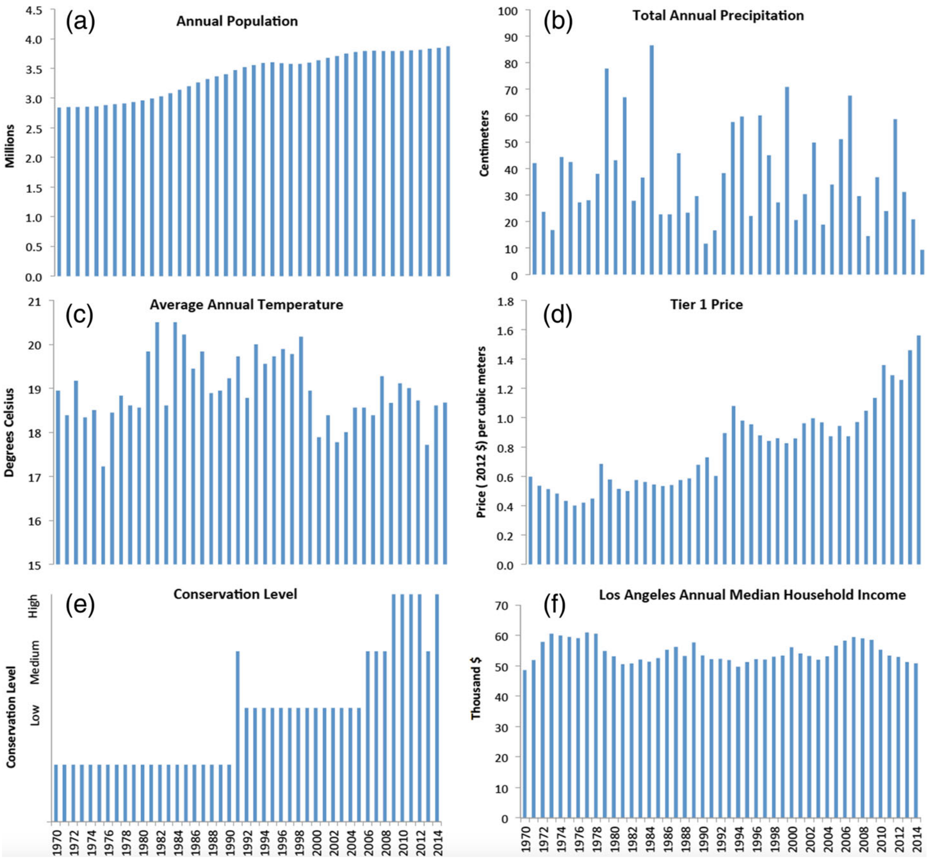

Fig. 2 Values of explanatory variables in the MLR models from 1970 to 2014

study are used to describe the effects of conservation, population, price, temperature, Los Angeles median household income, and precipitation, on water demand amongst Los Angeles consumer classes. MLR involves fitting a linear equation constructed with explanatory variables to the observed data presented to the model. Hence, every observation consists of the full set of explanatory variables and the corresponding dependent variable, with multiple linear regression coefficients chosen for the former to estimate the latter with least square errors. In this study, seven multiple linear regression models were developed to understand the variables that impact each demand category as well as the seasonality of residential water demand.

Equation (1) shows the hypothesized dependence of water demand (Y_t) on the explanatory variables. The regression models were fitted using all monthly and yearly data from 1970 to 2014 for water demand and the explanatory variables.

$$\begin{aligned} Y_t &= \beta_0 + \beta_1(Tier1price) + \beta_2(Tier2price) + \beta_3(population) \\ &+\beta_4(precipitation) + \beta_5(temperature) + \beta_6(LAmedianhouseholdincome) \\ &+\beta_7(lowconservation) + \beta_8(mediumconservation) + \beta_9(highconservation) \end{aligned} \tag{1}$$

2.3 Goodness of Fit Metrics

The relative performance of the MLR models was evaluated using three different parameters: R^2, MAPE, and NRMSE. To compare monthly and yearly models, monthly values for MAPE and NRMSE were accumulated for each year and compared with the yearly models.

2.3.1 Mean Average Percent Error

Mean average percent error reflects the average error on a fractional basis. It is computed using the following equation:

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\hat{y}_i - y_i}{y_i}\right| \tag{2}$$

where y_i is the actual water demand, $\hat{y}_i$ is the predicted water demand obtained from the model, and n is the number of observations. Water demand models with lower MAPE values perform better than those with larger values for MAPE.

2.3.2 Coefficient of Determination

The coefficient of determination is an indicator of the relationship between the observed and predicted results in a model. This goodness of fit parameter shows what amount of the total variation in the model is due to the explanatory variables and the strength between the linear association of water demand and the explanatory variables. Therefore, the higher the R^2 the better the goodness of fit. The coefficient of determination is calculated as follows:

$$R^2 = \frac{SS_{regression}}{SS_{Total}} = \frac{\sum_{i=1}^{n}\left(\hat{y}_i - \overline{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \overline{y}_i\right)^2} \quad \text{and} \quad \overline{y}_i = \frac{1}{n}\sum_{i}^{n} y_i \tag{3}$$

where $_i$ is the mean water demand, and SS is the sum of squares of residuals. The coefficient of determination varies over the range of 0 and 1 and is calculated for each of the alternative models developed in this study.

2.3.3 Normalized Root Mean Square Error

The normalized root mean square error describes the average prediction error, with larger errors given greater weight in the calculation. Lower values of NRMSE indicate less residual variance. It also allows for the comparison of models with different scales, which is necessary for water demand categories that vary. The equation used to calculate NRMSE is given by

$$NRMSE = \frac{RMSE}{y_{max} - y_{min}} \qquad RMSE = \sqrt{\left(\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2)}{n}\right.} \tag{4}$$

The numerator in the expression inside the square root is equivalent to the total sum of square errors for the model.

3 Results and Discussion

The performances of the multiple MLR models were compared using SPSS 22.0 (SPSS 2013). Seven separate models were developed considering the same averaging time and explanatory variables associated with the consumption categories. Results of the analysis demonstrate the variation of factors that impact water demand in Los Angeles based on residential, commercial, industrial, and governmental water use.

3.1 Significance of Each Variable in the Model

Initially, all variables were included in the analysis: Tier 1 and Tier 2 pricing structure, median household income, population, precipitation, temperature, and level of conservation. To check for collinearity, the variance inflation factors (VIF) for each variable were calculated and a correlation matrix was developed, which can be seen in Table A1 in the Online Resource. The VIFs for some of the variables in Table A1 were higher than 5 indicating collinearity between variables, especially Tier 1 and Tier 2 pricing structure. To remove collinearity, Tier 2 was removed from the explanatory variables.

The multiple linear regression was calculated again with median household income, population, conservation level, temperature, precipitation, and Tier 1 price. The VIF values were all below 5 indicating low collinearity levels (Table A2). After running each regression, coefficients and standard errors were observed. All significant variables with p-values below 0.05 were kept in the regression models. The values and performance for the MLR modeling results, including the non-significant variables and their standard errors are displayed in Table A5 and Figure A4 of the Online Resource. Equations 5–11 shows each regression model with only significant variables ranked in order of highest R^2 value. Results of the regression models indicate the various differences between the consumer classes.

$$\begin{aligned} MFD\left(m^3\right) = & -4.87E8 - 1.15E8(WP1) + 2.42E2(P_M) - 3.87E7(C_L) \\ & -5.27E7(C_M) - 5.57E7(C_H) - 1.94E3\,(MHI) \end{aligned} \tag{5}$$

$$RD_Y\left(m^3\right) = -7.52E5(R_M) - 1.50E8(WP1) + 2.14E2(P_M) \\ -3.44E7(C_L) - 4.47E7(C_M) - 6.18E7(C_H) \tag{6}$$

$$CD\ \left(m^3\right) = -1.32E5(R_M) - 3.24E7(WP1) \\ +1.36E1(P_M) + 6.52E2(MHI) \tag{7}$$

$$RD_M\left(m^3\right) = -6.68E7 + 1.34E6(T_M) - 7.46E4(R_M) - 1.23E7(WP1) \\ +2.78E1(P_M) - 5.49E6(C_L) - 8.74E6(C_M) - 1.03E7(C_H) \tag{8}$$

$$ID\left(m^3\right) = -1.69E8 + 4.06E6(T_M) - 2.17E7(WP1) + 4.63E1(P_M) \\ -1.99E7(C_L) - 2.05E7(C_M) - 1.92E7(C_H) \tag{9}$$

$$GD\ \left(m^3\right) = -7.36E6(R_M) - 1.26E5(WP1) \tag{10}$$

$$SFD\ \left(m^3\right) = 4.98E8 - 6.29E5(R_M) \tag{11}$$

As shown in Eq. (5), temperature and precipitation were not significant in impacting water demand for multi-family households since these housing properties have lower outdoor water demand. Multi-family consumers were however highly affected by price increases, median household income, conservation levels, and population. Lower income households are more likely to live in multi-family units (Santamouris et al. 2007) and are sensitive to water price increases, fluctuations in income, and changes in population. A one-person increase in population in the model yields a 242 m^3 increase in multi-family water demand per year. A one-dollar per m^3 increase in Tier 1 water price would decrease multi-family water demand by 115,000,000 m^3 per year. Compared to a very low level of conservation, a low conservation level decreases water demand by 38,700,000 m^3 per year, a medium conservation level decreases water demand by 52,700,000 m^3, and a high conservation level decreases water demand by 55,700,000 m^3 per year. Finally, a one-dollar increase in median household income in Los Angeles decreased multi-family water demand by 1,943 m^3 a year.

The yearly total residential MLR model, Eq. (6), indicated that population, precipitation, and conservation were statistically significant. However, temperature and median household income were not significant. Annual average temperatures from 1970 to 2014 did not fluctuate to the extent to which it did on a monthly basis over those years indicating a lack of seasonality being represented in the yearly model. The yearly model shows that a one-person increase in population yields a 214 m^3 increase in residential water demand per year. A one-centimeter increase in precipitation would decrease water demand by 752,000 m^3 per year while a one-dollar per m^3 increase in Tier 1 water price would decrease residential water demand by 150,000,000 m^3 per year. As for conservation, a low conservation level decreases water demand by 34,400,000 m^3 per year, a medium conservation level decreases water demand by 44,700,000 m^3, and a high conservation level decreases water demand by 61,800,000 m^3 per year compared to very low levels of conservation for the residential sector.

Commercial water demand was sensitive to median household income, price, population and precipitation. The explanatory variable population indicated that a one-person increase in population in the model yields a 13.6 m^3 increase in commercial water demand per year, as shown in Eq. (7). As for precipitation, a one-centimeter increase in precipitation would decrease water demand by 132,000 m^3 per year. A one-dollar per m^3 increase in Tier 1 water price would decrease commercial water demand by 32,400,000 m^3 per year whereas a one-dollar increase in median household income in Los Angeles increased commercial water demand by 652 m^3 a year. When median household income increases in Los Angeles, the commercial sector is observed to raise its usage of water. This association could be due to increased demand for commercial goods by consumers when their incomes are higher.

For the monthly residential water demand model (Eq. 8), all explanatory variables except median household income were significant in impacting water demand. As shown in Eq. (8), a one-person increase in population in the model yields a 27.8 m^3 increase in residential water demand per month. As for climate variables, a one-centimeter increase in precipitation would decrease water demand by 74,600 m^3 per month. This is reasonable, as increased rain would dissuade people from using water for outdoor landscaping, which is responsible for over 30 % of total residential water demand as noted earlier. For temperature, a one-degree Celsius increase would increase residential water demand by 1,360,000 m^3 each month. This could be explained by the fact that rises in temperature increase water demand for outdoor purposes (Chang et al. 2014). A one-dollar per m^3 increase in Tier 1 water price would decrease water demand by 12,300,000 m^3 per month. As for conservation, a low conservation level decreases water demand by 5,490,000 m^3 per month, a medium conservation level decreases water demand by 8,760,000 m^3, and a high conservation level decreases water demand by 10,300,000 m^3 per month compared to very low levels of conservation. This indicates that the amount of conservation increases by 59 % from low to medium conservation and increases an additional 18 % from medium to high levels of conservation.

Price, population, temperature, and conservation level were significant for the industrial category, whereas precipitation and median household income were not. As shown in Eq. (9), as the population of Los Angeles increases by an increment of one, industrial water demand grows by 46.3 m^3 per year. For temperature, a one-degree Celsius rise increases industrial water demand by 4,060,000 m^3 each year whereas a one-dollar per m^3 increase in Tier 1 water price would lower industrial water demand by 21,700,000 m^3 per year. Compared to very low levels of conservation, low conservation level decreases water demand by 19,900,000 m^3 per year, a medium conservation level decreases water demand by 20,050,000 m^3, and a high conservation level decreases water demand by 19,200,000 m^3 per year. This suggests that industrial water use reductions due to conservation may have occurred with the initial introduction of low levels of conservation, without further reductions achieved since then. However, no adjustments are made here for changes in the type and level of industrial activity in the service area, so strong inferences regarding temporal changes in industrial water use efficiency are not possible.

The governmental category showed high sensitivity to precipitation and price. Equation (10) shows a one-centimeter increase in precipitation contributes to a decrease in governmental water demand by 7,360,000 m^3 per year. Since the watering of parks is under the governmental category water demand, increases in precipitation drives down water demand for that category. Additionally, a one-dollar per m^3 increase in Tier 1 water price would decrease governmental water demand by 126,000 m^3 per year.

Precipitation was the only significant variable in the single-family residential yearly model, as a one-centimeter increase in precipitation would decrease water demand by 629,000 m^3 per year. Single-family houses have higher water demands for outdoor purposes, such as watering lawns. Increases in precipitation therefore decrease the amount of water needed for outdoor use. All other consumer classes were impacted by price except for single-family residents. This could be because individuals who live in single-family homes may have higher incomes and are less affected by increases in water price.

Overall, the results of the linear regression models demonstrated that different factors are dominant for each water demand category. Median household income did not impact water demand in most of the models, which could be due to median household income in Los Angeles not fluctuating greatly over the years (Fig. 2). One way to better understand median household income is to analyze spatial rather than temporal variability. Such data were not available for analysis during the allocated time period. Increases in water price were seen to decrease water demand in all categories, which is comparable to previous studies (Gaudin 2006; Rinaudo et al. 2012). Price clearly has been an effective tool for conservation of water. Additionally, the monthly water demand model showed seasonality trends with temperature that would not have been seen in the yearly models. Similar to previous literature (Billings and Jones 2008; Jain et al. 2002), the monthly MLR model demonstrates that increases in precipitation and decreases in temperature drive down water demand. The results of the analysis can be used by decision makers as tools to inform water demand reduction strategies in each consumer category.

3.2 Performance Analysis Metrics of Monthly and Yearly Water Demand Models

Model performances were evaluated using coefficient of determination, MAPE, and NRMSE. Figure 3 displays the MAPE, NRMSE, and R^2 performance metrics for the seven models. Out of all seven models, multi-family residences had the highest R^2 of 0.94 indicating that 94 % of the variability of monthly water demand was explained by the linear relationship with the explanatory variables. The single-family model, on the other hand, had the lowest R^2 of 0.14 due to only one of the explanatory variables, precipitation, being significant in the model.

For MAPE and NRMSE, total yearly residential water demand model has low residual variance and mean average percentage error compared to the other six models, although the multi-family model has a lower NRMSE and the commercial model has a lower MAPE. As for the commercial and government category, the MAPE is low while the NRMSE is not; indicating that the errors of the parameter estimates are low while the errors regarding the fit of the model are high. The R^2, NRMSE and the MAPE values provide general indications of model fit, since they are dimensionless and not affected by scale of unit differences between the dependent variables.

3.3 Counterfactual Effects of Price and Conservation on Predicted Annual LA Water Demand

To understand better the influence of demand management policies on residential water use, consider how the residential demand in Fig. 1 might have differed over recent decades had the conservation efforts and price increases implemented by LADWP not taken place. To illustrate such a counter-factual analysis we used the monthly model (RD_M) to predict water demand with and without the conservation level and pricing changes implemented after 1990. For the prediction without these changes the price was fixed at 1990 levels and the total annual conservation was kept at zero. The

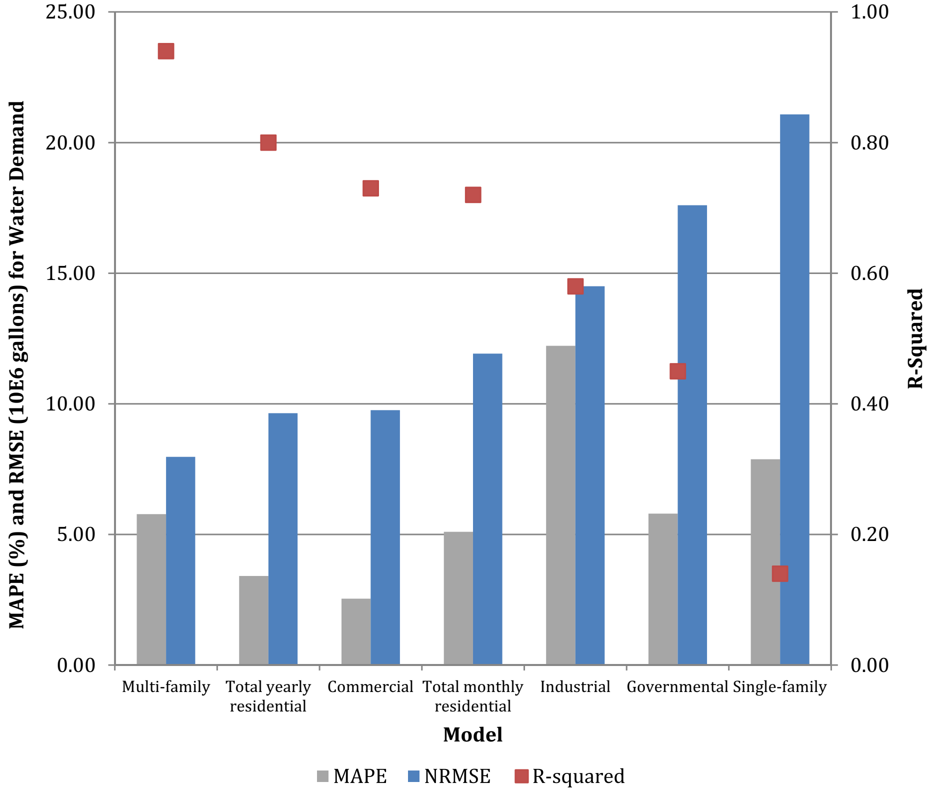

Fig. 3 Performance measures for the seven multiple linear regression models

results are shown in Fig. 4 using aggregated monthly data points to show the yearly variation in water demand. As indicated, the fit of the full model (green line) to the observed water demand (blue dashed

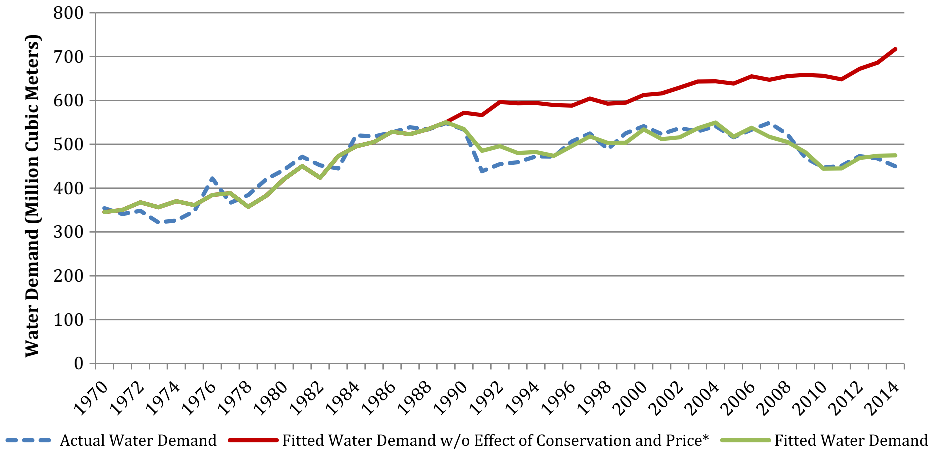

Fig. 4 Effects of price and conservation on predicted annual Los Angeles water demand. *Monthly multiple linear regression model, RD_M, fit to observations 1970–2014, estimated demand with constant price and no conservation shown for 1990–2014

line) with conservation and pricing inputs properly considered throughout the 1970–2014 study period was very good throughout. However, when price was fixed and conservation set to zero, the model prediction (red line) continued along the upward trend exhibited during the first half of the study period, influenced predominantly by population growth. The growing difference between the red and green lines in Fig. 4 thus provides an estimate of the influence of the LADWP pricing and conservation policies in offsetting the effects of population growth.

Conservation level was used as an explanatory variable to analyze the overall water demand in Los Angeles with and without its effects. As seen in Fig. 4, conservation effort, along with price play a large role in reducing water demand even with increases in population. Additional research is needed to improve understanding of the impact of conservation, technology, and communication programs and price policies in Los Angeles. Identifying these impacts will allow for better water demand management and planning of future water supply in Los Angeles.

4 Conclusions

The purpose of this study was to develop and evaluate various models with application to water demand data for Los Angeles, California in order to identify important factors impacting each water demand category. Multiple linear regression models were developed and used to fit historical (1970–2014) water demand data for Los Angeles for residential, commercial, industrial, and governmental water demand. Both monthly and yearly residential models were developed to indicate seasonal effects on water demand.

Results for individual demand categories demonstrated that price was significant in impacting water demand for all categories except for single-family households. Although multi-family residences had the highest R^2 of 0.94, the single-family model had the lowest R^2 of 0.14 due to only one of the explanatory variables, precipitation, being significant. Water price in the various categories consistently decreased water demand indicating that price is an effective tool for conservation of water. The impact of conservation was significant in all demand categories except commercial, governmental, and single-family households. The number of conservation measures and estimated levels of hardware and non-hardware conservation was shown to decrease consistently overall water demand.

The monthly MLR model examined the effect of seasonal changes in temperature and precipitation on residential water demand and demonstrated that increases in temperature and decreases in precipitation have increased water demand, which is consistent with the literature. The yearly water demand MLR models analyzed the differences between single-family, multi-family, commercial, industrial, and governmental water demand categories. Taken together, the results of the MLR models show that although climate and population have had a strong influence in increasing monthly total residential water demand, the impacts of conservation and price since 1990 have counteracted this increase. The variables affecting water demand vary both spatially and temporally and are subject to numerous stressors, including climate change.

This study is novel in using a large water demand dataset for Los Angeles to distinguish the differences among demand categories, monthly vs. yearly effects of climate, and counteracting impacts of price and conservation on population growth and climate. Future urban water demand research however should aim to include better indicators for socioeconomic status and geospatial data. These types of data were not available for this study.

Understanding the underlying drivers of urban water demand can help inform planning for the sustainability of water supply systems, such as that of Los Angeles, in the future. Further, development of such models will enable better forecasting of water demand under changing conditions of climate, population, and economy.

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