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Decadal review of residential water demand analysis from a practical perspective

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Abstract

Residential water demand has been extensively studied over more than four decades, but as yet there is no consensus on the best or most appropriate model from a practical perspective. Conservation and sustainability programs with new metering incentives have increased the necessity for an easy to use forecasting model for water resource management based on a better understanding of the factors driving residential water demand. Analytical techniques have increased in complexity, advancing with new tools for computing and data collection such as GIS and remote sensing. This paper presents a decadal review of how the residential water demand analysis have evolved over time with changes in price policies, conservation attitudes, technological improvements, and other factors explaining water demand. This paper will help provide the knowledge base for the future studies and recommendations are made for addressing/bridging the gap between drinking water industry and research community.

Key words: residential water demand analysis and water price, water conservation

INTRODUCTION

Supplying residential water when and where it is needed is a critical area given today's rapid population growth, fluctuating water use patterns, climate change, new environmental awareness, and increasing expense for water resource projects (Brookshire *et al.* 2002; Jenkins *et al.* 2003; House-Peters *et al.* 2010). Decades of research has revealed that residential water demand is a function of various factors including population demographics, water pricing, regulations, house characteristics, weather, and emotional and psychological drivers in consumer habits and attitudes.

Future water resource management must meet this demand flexibly by implementing both conservation and sustainable practices. To gather information to support practical sustainable policies nationwide, residential water meters are being introduced in many areas to help pinpoint areas of high water demand and highlight areas where recycled or reused water may offer a viable alternative (Friedman *et al.* 2011). Accurate water demand analysis and associated modeling efforts are also vital for designing/operating water distribution network and treatment systems and identifying appropriate water resources (Filion *et al.* 2007).

Residential water demand has been extensively studied over more than four decades and the number of journal articles published has continued to increase, appearing in technological and academic publications across several different disciplines. In Figure 1, keywords of 'residential water demand' was used and the number of publications from each decade are plotted. It is clear that research efforts have been increasing exponentially. Since the 1970s, water resource management

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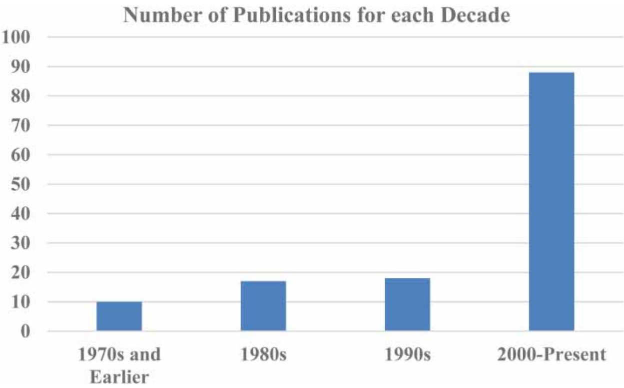

Figure 1 | Number of publications for each decade (from Web of Science, keywords using 'residential water demand').

has shifted towards water conservation and demand-side management, and multi-disciplinary collaborations between engineers, economists, sociologists and urban planners are now common. Advances in technology now permit finer grained measurement of water consumption and new household appliances have far greater water efficiency. Residential water demand analytical techniques have increased in complexity, with faster, more powerful computational programs, and demand side management tools have been introduced that decrease water demand (Inman & Jeffrey 2006; Hurlimann *et al.* 2009; Tanverakul & Lee 2015).

This paper presents a decadal review of how the residential demand analysis have evolved over time (from 1970s until present) with changes in price policies, conservation attitudes, technological improvements, and other factors explaining water demand. In addition, advances in analytical techniques related to residential water demand, including theories, practical methods, technologies, and conservation policies are discussed chronologically. There are several review papers focusing on residential water demand modeling/ estimation/ conservation issues (Arbués *et al.* 2003; Dalhuisen *et al.* 2003; Inman & Jeffrey 2006; Worthington & Hoffman 2007; House-Peters & Chang 2011), but none of them has focused on decadal/ chronological review of residential water demand analysis from a practical perspective. This paper will help provide the knowledge base for the future studies in residential water demand analysis and recommendations are made for addressing/bridging the gap between drinking water industry and research community.

DECADAL REVIEW

1970s and earlier

Decadal major theme

In the beginning, water demand was estimated by multiplying average daily demand per person with the estimated population (Hanke 1970; Oh 1971). This is based on the assumption that water price changes will not affect the water demand because water is crucial for human's basic needs. Prior to the sixties, this view was unquestioned by water managers, whose solution to low supply was simply to find a larger water source (Grunewald *et al.* 1976). However, this become unacceptable as the cost of supplying water began to increase in response to transmission and distribution costs, especially in metropolitan centers (Cassuto & Ryan 1979), and expenses were exceeding revenues due to inflation (Foster & Beattie 1979). During the 1970s, however, water started to be regarded as an economic good, which could then be managed through pricing policies (Kim & McCuen 1977; Mitchell & Leighton 1977; Cassuto & Ryan 1979). The effect of price on residential water

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demand was described in terms of price elasticity, which will be explained later in this section (Howe & Linaweaver 1967). In Figure 2, decadal major theme of how residential demand analysis have evolved over time with changes in price policies, conservation, water efficiency practices/technologies, theories/modeling techniques are summarized chronologically.

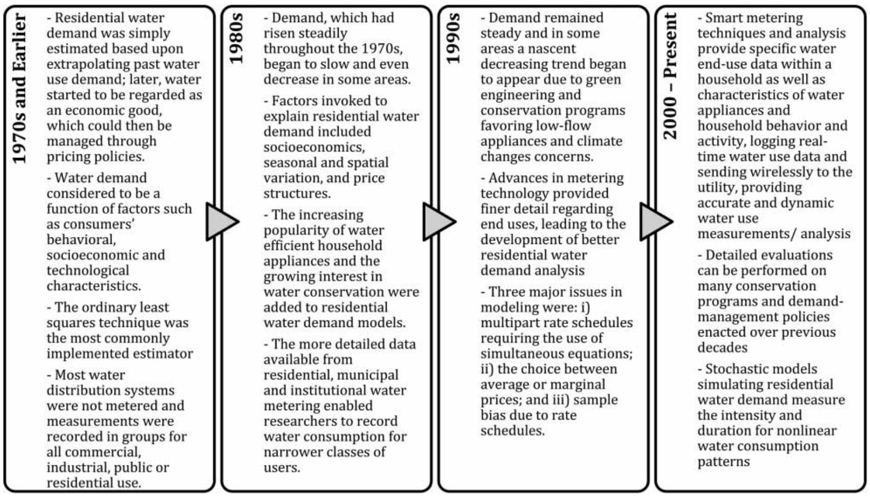

Figure 2 | Major decadal theme of residential water demand analysis.

Analytical developments

Using econometric concepts, water demand became a function of factors such as consumers' behavioral, socioeconomic and technological characteristics. In order to define these qualitative factors and quantify their impact, multiple regression analysis was used to test whether a dependent variable, in this case water demand, is related to more than one independent variable. Multi-linear regression models can simultaneously estimate the individual impact an explanatory variable has on residential water demand, resulting in a valuable forecasting tool. Independent variables or predictors (X_i) are chosen for their assumed impact on the dependent water demand variable (Y). The multi-linear regression model with n number of explanatory variables can be generalized as follows:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_n X_{ni} + \varepsilon_i$$
$$\varepsilon_i = \mu_i + \eta_i$$

An additive error is added to the model representing unobserved influences consisting of two parts. The first term μ_i covers random unobserved influences and assumed to be normally distributed, tending towards zero. The second term η_i represents effects that were unobserved.

Most researchers applied the same independent variables (i.e. factors), namely the price of water, number of people in the household, household income, lot size, whether they had a swimming pool, and some climatic data (Morgan & Smolen 1976). The ordinary least squares (OLS) technique was the most commonly implemented estimator and functional forms of the demand curve were either linear, double-log, or log-linear (Grima 1973). This was to better fit the observed demand data. Explanatory factors thought to influence residential water demand were assigned as independent variables, with some researchers using binary variables for items such as swimming pools or sprinkler systems (Morgan 1974), and hypothesis testing performed to test the significance of the proposed independent variables.

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Water use data for residential demand models came from various levels of aggregation within a city or region. Telephone and mail surveys collected information on the water demand habits and attitudes of residential consumers (Howe & Linaweaver 1967). At this time, most water distribution systems were not metered and measurements were recorded in groups for all commercial, industrial, public or residential use (Howe & Linaweaver 1967; Sharpe 1978). Some locations measured the amount of water consumed while others recorded the amount of water supplied, so any losses along the distribution system had to be extracted from the amount of water actually used. Also, the available data only provided average monthly or yearly data and then not for substantial lengths of time, so the analytical results were not precise enough.

Howe & Linaweaver (1967) were the first to disaggregate data between domestic and (outside) sprinkler uses. They also used time series data to study residential water demand. Time series model was utilized for the time series component of the residential water demand data to forecast future water demand. This approach assumes that all values of the variable represent measurements at equally spaced time intervals and that closer observations have a stronger dependency. Since the data are interdependent, autocovariance and autocorrelation can be used to measure the dependency among the variables in the time series (Box & Jenkins 1976). So, the time series analysis was applied to identify patterns and forecast future values from the historical data. Most research incorporated only either time-series or cross-sectional data with only a few using both data sets in attempts to eliminate the broad errors of either too short a time period or samples that were too small or too uniform (Morgan 1974; Cassuto & Ryan 1979).

Price Water utilities responsible for delivering water need to set water rates such that sufficient revenues generated to cover their capital and operating costs (Gysi 1972). For public utilities, prices are often affected by politics and subsidized by tax money (Grunewald *et al.* 1976). Price structures vary widely between regions, generally falling into one of three categories: flat rate, increasing block or decreasing block rates, each with an accompanying fixed water service fee. Flat rate pricing imposes a single volumetric price for all users, regardless of use, while block rates charge different prices according to the amount used after a set base level. Increasing block rates increase with increasing volume use, whereas the unit cost for decreasing rates goes down as the volume used increases.

According to the law of demand in economics, all other things being equal, increasing the price of a commodity should result in a decrease in quantity demanded. The demand reduction associated with an increase in price is termed the price elasticity of demand (Mays 2010). However, residential water use is a unique product since it has no replacement for basic needs such as bathing, drinking, and washing. So, increasing the price should result in a negative elasticity based on the marginal utility of residential water, which is initially high when fulfilling basic needs such as drinking, bathing and cooking, but rapidly decreases to a negative utility once those basic needs are covered (Grima 1973).

Price elasticity can also be affected by price structure, as in the case of decreasing block structures or low flat rates that tend to result in positive elasticities for water demand (Gysi 1972; Cassuto & Ryan 1979). Generally, water has been shown to have a negative elasticity, although some studies have reported a relative inelasticity of water with price (Howe & Linaweaver 1967). When separated into inside and outdoor water demand, outdoor use was found to be elastic and greater in the west than the east. The use of sprinklers, on a municipal level appears to be highly influenced by price (Morgan & Smolen 1976) and changes in water demand after a price change are greater with longer periods of adjustment (Howe & Linaweaver 1967). Increasing price to reduce residential water demand also reduces the revenue received by the water utilities, but this can be recovered through price structure and marginal cost pricing (Sharpe 1978). Gysi (1972) suggested that price should remain flexible over time to accurately reflect low flow conditions and thus decrease demand at such times. Price elasticity analysis started to gain popularity as one of important water policy oriented research domains considering their significant impacts on water demand.

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Geography and Weather Most studies in the 1970s recognized the effect of local weather on residential water demand analysis. Morgan (1974) included a variable for temperature and precipitation to account for seasonal variation, while Howe & Linaweaver (1967) used evapotranspiration as a climatic variable in their regression analysis. Intent on determining the most appropriate regression estimator to represent climatic variation, Morgan & Smolen (1976), tested three estimators–temperature and precipitation, potential evapotranspiration, and monthly seasonal variables–but found that although temperature and precipitation were useful for normalizing climatic influence in water demand studies, consumers also respond to their perception of evapotranspiration rates, the temperature-humidity index. Wong (1972) confirmed the importance of summer temperature in a time series analysis of urban water demand in Illinois.

Household Technological Shifts Installing low-flow fixtures has been shown to lower indoor residential water use (Sharpe 1978) and the major areas for reduction are the bathroom (75% of total), followed by the kitchen and laundry room (Kim & McCuen 1977). Batchelor (1975) included toilets, washing machines, showers, and garden sprinklers as variables in a residential water demand model and found a positive correlation between increasing household wealth and the increased likelihood of water efficient appliance installation.

Non-Price Conservation Programs Sharpe (1978) observed that in a short-term water crisis, reductions in residential water consumption are often temporary. Kim & McCuen (1977) recommended that reductions could best be achieved by combining pricing policies with regulations and an emphasis on low-flow technology. A flat rate structure offers little incentive for conservation and metering was recommended for demand reduction (Maki *et al.* 1978).

1980S

Decadal major theme

In the 1980s water demand, which had risen steadily throughout the 1970s, began to slow and even decrease in some areas. Although the bulk of reduction was in agricultural and industrial areas, residential demand was also declining due to more efficient household appliances, the increase of multifamily homes with smaller yard and growing public awareness (Browne *et al.* 1980). Factors invoked to explain residential water demand included socioeconomics, seasonal and spatial variation, and price structure. Socioeconomic determinants of water use began to be viewed as more important, along with individual knowledge and attitudes towards water price and quantity of water use. Price elasticity of water demand remained a popular research topic through the 1980s as the cost of supplying water continued to rise while the cost to the consumer remained flat.

The increasing popularity of water efficient household appliances and the growing interest in water conservation were added to residential water demand models (Grisham & Fleming 1989). The more detailed data available from residential, municipal and institutional water metering enabled researchers to record water consumption for narrower classes of users (Griffin *et al.* 1981). Water utilities began recording water use on less aggregated levels, and the USGS gave domestic water its own classification in its 1985 report, which included normal household use and outdoor watering, and discussions of meter installation and operation began to appear in the technical literature.

Analytical developments

Utilizing the new water metering and disaggregated water use data, improved models were proposed that used more accurate data and separated out indoor and outdoor use (Power *et al.* 1981). Time periods were also refined in time series models that could handle monthly water demand, while the effects of trend, seasonality, autocorrelation and climatic correlation were removed in time

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series cascade models (Maidment & Parzen 1984) for identifying patterns and forecast future values from the historical time series data. Time series analysis in conjunction with multiple regression analysis was used to test the effectiveness of water conservation programs by comparing before and after receipt of the conservation kits such as showerheads, aerator, etc. (Morgan 1982).

Price In response to the use of an average price by Foster & Beattie (1979) in their regression model for water demand, Griffin *et al.* (1981) noted that this did not take into account the complexity of rate structure and was not closely related to the marginal price faced by consumers and proposed instead the use of a marginal price calculated from customer billings. Statistical studies revealed a strong correlation between lower water use and a greater understanding of price rates (Chicoine & Ramamurthy 1986; Agthe *et al.* 1988). Since under tiered rate structures, the price faced by consumers is based on quantity of water use, price is endogenous, and violates the assumption in simple OLS of independent variables being uncorrelated with errors. Also, there is the issue that under tiered rates, customers have to make two choices; what block of consumption to consume within and how much to consume within the block. Several methods have been used to address this problem, among those most popular include instrumental variable models (IV).

IV estimation addresses the problem of endogenous price variables with an instrument variable that is highly correlated with the price variable, but uncorrelated with the error term. In a two-stage variable estimation technique, the first-stage consisted of estimating water demand on the set of actual marginal prices faced by each household. Next, that predicted water consumption estimation is used to calculate the predicted marginal price and a predicted difference. The difference variable is found from subtracting the marginal price from the average price and multiplying by the demand. Once the instrument price variables are found, they are used as independent variables in the demand model to estimate water consumption.

Previous studies had ignored the effect of price structure on price elasticity, but Nieswiadomy & Molina (1989) tackled the issue directly, investigating the decreasing and increasing block rate structures by comparing the OLS and IV. Estimates of income elasticity were also included in the literature but almost income inelastic and small in magnitude (Chicoine & Ramamurthy 1986; Moncur 1987).

Geography and Weather Weather variables in water demand functions became more refined, including the addition of evapotranspiration matched to the billing cycle of consumers (Nieswiadomy & Molina 1989). Wilson (1989) argued for the introduction of a climate variable in water demand analysis, which he found to be the most important predictor of western sprinkler demand that was metered.

Household Technological Shifts The number and type of household appliances is important in modeling residential water demand. Examining the effect of household appliances on water demand, Clouser & Miller (1980) added binary variables representing a dishwasher and washing machine to their model. By the 1980s most U.S. homes already had automatic clothes washers and dishwashers and older appliances were being replaced with more water efficient machines such as low flush toilets. This largely accounts for the decreases in water consumption in the 1980s following the increases in residential water demand in the 1950, 60 and 70 s when water intensive appliances were first entering homes in large numbers (Browne *et al.* 1980).

1990S

Decadal major theme

Smaller household sizes, increasing household incomes, conservation programs and population migration have all contributed to the stabilized and slowly decreasing residential water demand (Diamond & Moezzi 2000). Advances in metering technology provided ever finer detail regarding residential water end uses, leading to the development of better residential water demand analysis

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(Schneider & Whitlatch 1991). Household appliances and their respective water load profiles began to be used to generate account information on water intensive appliance size and capacity and flow rates, a non-intrusive and simple technology was introduced to classify water demand into specific end uses by plotting flow intensity over time for each appliance (Fiebig *et al.* 1991).

Analytical developments

Although the disaggregation of data for modeling water use was made possible by the finer data becoming available and the growth in metered consumption, most studies in the 1990s still relied on data that combined various levels of aggregation (Hewitt & Hanemann 1995). Reviewing recent household water demand methods, Bachrach & Vaughan (1994) outlined three major issues: (i) multi-part rate schedules requiring the use of simultaneous equations. That is, price of water determines water quantity demanded and price is determined by consumer consumption; (ii) the choice between average or marginal prices; and (iii) sample bias due to rate schedules.

Expanding on traditional household electricity load profiling, Fiebig *et al.* (1991) reformulated conditional demand analysis into a random coefficient model (RCM) to allocate household water use into respective appliance or end-use. Prior regression models handled the presence of water intensive appliances by using fixed dummy variables that ignored variations in size and capacity across households, but RCM treats appliance variables as random and allows for the direct use of metering data. By creating a model that uses direct metering data, accurate estimates of load profiles was produced with direct appliance metering.

Price As the population grew so did water demand, and as more regions became water stressed the marginal price of supplying water was driven upwards (Nieswiadomy & Cobb 1993). Marginal price can differ markedly for peak and off-peak periods as the marginal cost to supply the water increases during peak or drought periods. In the short-term, peak periods have greater negative price elasticity for water demand, but the reduction in water demand from price increases will adjust and demand will increase again in the long-term (Lyman 1992; Wang *et al.* 1999). Water resource management strategies that previously relied on educational programs and outreach to promote conservation and sustainability began to turn to pricing as the key to decreasing residential demand (Nieswiadomy & Cobb 1993).

Increasing block rates lower water demand by charging customers more based on higher water use (Pint 1999), but this was not the most common strategy adopted. A 1996 survey by AWWA found the residential rate structure distribution in the U.S. to be: 39% uniform; 33% declining block: 22% increasing block; and 4% flat, even though the increasing block rate is known to be most effective at targeting high volumes and discretionary use such as gardening during peak demand periods (Jordan 1994). Stevens *et al.* (1992) found that different price structures had no effect on water use if the price charged was close to cost of supplying. Nieswiadomy & Cobb (1993) also suggested that increasing block structures are not solely responsible for decreasing water demand because cities that implement increasing block rates are those that are already conservation minded.

Geography and Weather Responding to deficiencies in the common linear regression treatment of climate, Miaou (1990) proposed a nonlinear model that separates base use from seasonal use that is better at reflecting water use variations and estimating summer demand under various climatic conditions. Climate change raises uncertainty regarding water supply capacities and demand fluctuations (Frederick & Major 1998), so utility managers and policy makers need a flexible management strategy for their existing infrastructure and in some areas could justify the construction of dams and levees, reservoirs, canals, and pumps. Future water demand will need to be estimated to design and maintain new infrastructure, and a climate impact variable should be included in residential water demand analyses (Frederick 1997). In a survey of water use models, Boland (1998) noted that as climate is so

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unpredictable and global climate models do not predict on a local level, a climate function for residential water demand models may be of only limited utility.

Household Technological Shifts Water price increases generally reduce water demand, but the installation of low-flow household appliances produces greater reductions in medium to long- term water use than price alone (Cameron & Wright 1994). An end-use survey confirmed that toilets are still the dominant indoor water consumers in residential homes (DeOreo *et al.* 1996). Government mandates such as the Energy Policy and Conservation Act of 1992 increased the availability of water efficient appliances by requiring the manufacture of water-efficient toilets, showerheads and faucet fixtures. New domestic water meters allowed end-use load profiles and accurate appliance water use to be modeled (Fiebig *et al.* 1991) and measuring flow rates every ten seconds produced highly detailed water patterns that could be linked to specific household appliances (DeOreo *et al.* 1996).

Non-Price Conservation Programs Renwick & Green (2000) developed an econometric model to evaluate the effectiveness of non-price programs in reducing aggregate residential demand. Water use and cost data were obtained from agency-level mean monthly cross-sectional time-series for eight California water agencies for the period 1989–1996. They considered six types of conservation programs: public information campaigns, subsidies or rebates for adopting water-efficient technologies, retrofit kits that included low-flow showerheads or dye tablets for leak detection, rationing or allocation programs imposing penalties for exceeding allocations, restrictions that put specific constraints on water use, and compliance programs that required households to file affidavits confirming water-efficient devices had been installed.

A study of alternative conservation measures designed to decrease residential water demand in Utah from 1992–1997 found significant negative estimated coefficients (i.e. effective in reducing water demand) from consumer education programs and the promotion of water efficient fixtures. In an analysis of time-series cross-sectional data across seven cities in three southwestern states covering the period 1984–1995, Michelsen *et al.* (1999) looked at the effectiveness of five types of non-price conservation programs in reducing residential water demand: public information programs, education (school) programs, retrofit programs, permanent ordinances and regulations, and temporary ordinances and regulations, finding reductions in residential demand ranging from 1.1 to 4.0%.

2000-present

Decadal major theme

In North America for the 2008 billing year, each individual household used 11,678 gallons less water than an identical household in 1978, corresponding to an approximately 13 percent decrease (Coomes *et al.* 2009). Smart metering techniques and analysis can provide specific water end-use data within a household as well as characteristics of water appliances and household behavior and activity, logging real-time water use data in individual homes and then transmitting it wirelessly to the utility company, providing accurate and dynamic water use measurements (Giurco *et al.* 2010; Chen *et al.* 2011). With finer resolution of water use data, detailed evaluations can be performed on the many conservation programs and demand-management policies enacted over previous decades (Lee *et al.* 2011). Short term and long term residential water trends are influenced by different factors; weather can alter demand from year to year, conservation programs, emerging concerns for the climate changes and new pricing structures can result in short-term decreases and new low-flow appliances can produce long-term savings (Olmstead *et al.* 2007; Olmstead & Stavins 2009).

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Analytical developments

Stochastic models simulating residential water demand measure the intensity and duration for non-linear water consumption, which varies greatly throughout the day. With the development of mathematical/ statistical analytics and their rapid applications to residential water demand analysis, stochastic models enable identify demand patterns and forecast future values effectively from the historical datasets. Among them, Poisson Rectangular Pulse has been one of popular stochastic models to simulate residential water use. Alcocer *et al.* (2004) developed a Poisson Rectangular Pulse model to generate residential water demand patterns for individual households and at various points across the distribution network. Then, they verified their model by gathering instantaneous water use data from the flow meters. Garcia *et al.* (2004) simulated indoor residential water demand based on a rectangular pulse point process, verifying their model using historical continuous time series data to confirm a good correlation between daily peak demand, maximum hourly demand and daily total demand.

With better demand measurement capacities, panel data which combines both cross-sectional and time-series data was applied to demand analysis. A basic linear panel model has the general form:

$$y_{it} = \alpha_{it} + \beta_i X_{it} + u_{it}$$

where, y = *residential water demand*, i = household, t = time, α = intercept term, X = explanatory variables, β = coefficient, u = random disturbance term of mean 0. The simplest panel model assumes homogeneity among households and pools all time series data together across household and time. If differences across households exist, an unobserved model could be used, which separates the error term into two components with one individual specific and time invariant. The unobserved effects model has the general form (Croissant & Millo 2008):

$$y_{it} = \alpha + \beta X_{it} + \mu_i + \varepsilon_{it}$$

where, α = intercept term constant across time and household; β = coefficient constant across time and household; μ_i = individual error component independent of time; ε_{it} = idiosyncratic error.

When considering the unobserved effect models, the explanatory variables have a random or fixed effects (FEs). Choice of estimation model depends on the individual error whether the error is independent or correlated with the explanatory variables. If the individual error is correlated then a FEs model can be used that handles the error with a further set of parameters and allows the intercept to vary across households (Croissant & Millo 2008). The FEs panel regression model attempts to control for unobservable factors among each residence by assigning unique time invariant identifiers. A simplified form of a FE model is as follows (Hsiao 2003):

$$y_{it} = \alpha_i + \beta x_{it} + \mu_{it},$$

where $i = 1\ldots$, N, over a time period $t = 1\ldots$ T. In this case, the intercept value, α_i, is dependent on omitted factors specific to each household i that are possibly correlated with the chosen regressors, x_{it}. Any time invariant variables that may have an effect on consumption are absorbed into the intercept term, α_i. The error term, μ_{it}, represents effects from unique household factors that were both not accounted for and uncorrelated with identified regressors (x_{it}). When the individual error is uncorrelated with the explanatory variables, a random effect models should be used. Random effect models allow the intercept term to vary randomly.

Polebitski & Palmer (2010) used panel data to develop an urban water demand model. Using the census tract as their spatial unit, the model took advantage of highly disaggregated data to forecast water demand on a per capita basis for single-family homes within a census tract. In other studies,

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panel data was successfully used to separate spatial and temporal effects on residential water demand analysis (Bell & Griffin 2005), and Shandas & Parandvash (2010) linked water use consumption patterns to urban land-use patterns by applying multiple regression analysis to geographic information system (GIS) and water consumption data, which enabled advancing the computing capacities and data storage/collection. Lee & Tanverakul (2015) and Tanverakul & Lee (2015) used FE panel regression models to determine metering installations and price change impacts on residential water demand in California.

Price As in the previous decade, conservative pricing structures achieved greater water savings by implementing increasing block rate structures than uniform rates (Rawls *et al.* 2010). Price structures inevitably affect the stability of revenue for utilities, creating problems for future infrastructure planning and maintenance (Borisova *et al.* 2008), but Rawls *et al.* (2010) found this revenue instability only occurred with block structures composed of more than three different block rates.

Households with lower incomes show greater price responsiveness than wealthier household so increasing price as a policy to decrease demand will be more effective in lower income communities (Renwick & Green 2000). Interestingly, consumer equity among income classes appears to be affected by different rate structures. Comparing the price elasticities for water demand when marginal or average prices were used, Rawls *et al.* (2010) observed no consistent trends: indoor and outdoor water respond differently to price, but outdoor use was consistently more sensitive to price increases. Coomes *et al.* (2009) suggested this price sensitivity may encourage customers to fix leaking pipes. Setting water rates is a very complex multi-objective process that is aimed at sustainability for current and future generations, resource allocation & environmental efficiency, equity & fairness, cost recovery or financial stability, public acceptability and transparency (Klawitter 2003).

Multifamily buildings usually have a master water meter and the costs are divided between residents so individual bills are only indirectly related to the amount used, which do not encourage individual users to conserve. Demand analysis has tended to focus on single residential homes, but now water charges are increasingly assessed through sub-metering, allocated based on the number of residents or the size of the residence in square meters, or a hybrid approach that employs a ratio of metered water use (in a unit) to total use for all residents (Mayer *et al.* 2004). There are approximately 30 million multifamily housing units in the U.S. and they account for a substantial part of the nation's residential water demand (Mayer *et al.* 2006). Apartment dwellers are not responsible for appliances or piping repairs, so it is perhaps not surprising that building managers rather than individual residents are more responsive to price increases (Mayer *et al.* 2004). Mayer *et al.* (2006) recorded a 15% decrease in water demand in multifamily apartment units after the installation of individual water meters.

Geography and Weather Martinez-Espineira & Nauges (2004) noted that the occurrence of rain has a psychological impact, and so the number of rainy days rather than the actual precipitation amount has a greater impact on water demand. They also found that water demand is minimally affected by weather as consumption approaches non-discretionary level of use. The results signifies the importance of consumer perception of weather vs. actual water use. Gutzler & Nims (2005) found significant fluctuations in water demand during the summer in arid New Mexico, while House-Peters *et al.* (2010) reported that individual building tracts responded differently to seasonal water use during a drought period in Portland, Oregon, with tracts of newer homes using the greatest amount of outdoor water.

Household Technology Shifts Water-efficient appliances continue to become more efficient. This has been partly driven by government mandates such as the Energy Independence & Security Act of 2007: dishwashers manufactured after 2009 and clothes washers after 2010 must reduce their water usage to 30%. Lee *et al.* (2011) conducted a four-year longitudinal study evaluating the impact of water conservation programs on individual household water demand in a county in Florida. High efficiency toilet and clothes washer rebate programs were observed to have the greatest effect on

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reducing water demand, and customers that had more than one type of efficient appliance had higher water savings.

Tanverakul & Lee (2015) found out that installing water meters in locations where no meters previously existed combined with associated volumetric pricing policies decreases water use. For example, metering and volumetric rates reduced household water use by 54 gallons per day (gpd) in Bakersfield, 37 gpd in Chico, and 13 gpd in Visalia (Tanverakul & Lee 2015). Similarly, the City of Davis installed meters on nearly 10,000 homes and began a metered billing rate, effectively reducing per-capita water use by 18%.

Current metering technology includes use of automated meter reading (AMR), which is the technology of collecting consumption, diagnostic, and status data from meters remotely and automatically. AMR is used primarily for monthly customer billing and reduced operational costs. Building upon AMR technology is advanced metering infrastructure (AMI), which are systems that measure, collect, and analyze energy usage, and communicate with metering devices on request or on a schedule. AMR and AMI technology, commonly referred to as smart metering has the ability to read and record real-time water use measurements in individual homes and then transmit it wirelessly to the utility provider. Smart metering has proven to reduce water use through leak detection. For example, after converting to a smart metering system, the City of Santa Maria in California reduced their water losses from 6 to 2% (Godwin 2011). Mathematical models have been developed and applied to the smart water systems in a building scale (Lee & Chae 2015).

Non-Price Conservation Programs Urban water conservation has paralleled energy efficiency and conservation activities as efforts switch to demand-side management, education, rebates, and incentives (Diamond & Moezzi 2000). Long-term conservation programs face the problem of demand hardening – the more efficient a service area becomes, the more difficult it is to save more water during a shortage or drought. Successful conservation programs in the 1970, 80 and 90 s created a more water efficient population so further reductions have been harder to achieve since the millennium (Maddaus & Maddaus 2008). Additional resources are needed to reach higher levels of water savings, but rebate or incentive programs centered on technological improvements can be costly. Conservation policies and programs enacted at the same time to reduce water demand during peak periods or droughts need further research to reveal how they interact to decrease overall aggregate demand (Renwick & Green 2000). Kenney *et al.* (2008) showed that simply adding new conservation measures or increasing prices does not result in increased water savings; savings are not additive but work together in dynamically reciprocal ways.

Investigating the effect of combining pricing and non-pricing strategies in lowering consumption, Timmins (2003) found that a tax increasing the price of water consumption produced larger water reductions than mandatory low-flow appliance regulation alone. Restricting land use and limiting landscaping has a stronger impact on reducing water demand in higher income households, which usually have larger plots of land and maintain larger landscaped areas (Renwick & Green 2000).

CONCLUSIONS AND OUTLOOK

Residential water demand has been extensively studied over more than four decades, but as yet there is no consensus on the best or most appropriate model from a practical perspective. To help provide the knowledge base for the future studies and recommendations to address/ bridge the gap between drinking water industry and research community, a decadal review of how the residential water demand analysis have evolved over time (with changes in price policies, conservation attitudes, technological improvements, and other factors explaining water demand) has been thoroughly studied.

It was also found out that the residential water demand models have progressed from simple extrapolations to complex mathematical models requiring sophisticated computer programs. All models

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suffer from tradeoffs, generally concerning the availability of data. Residential water records from the 1960 and 70 s aggregated municipal and institutional data across regions collected from utilities that measured water use by the amount of water delivered. Now, through the use of smart metering, time and intensity of water use can be broken down into specific end uses and residential water use divided into smaller groups such as individual houses or census tracts. Dynamic effects such as micro weather patterns and climate change can now be modeled using fast workstations and GIS data and these more detailed datasets support far greater modeling precision, but the complexity and effort involved may only be appropriate for research purposes rather than practical management strategies.

Policies and programs that support water conservation have become more effective through the refinement of water demand measurements using household demographics. Price elasticity of water demand is a particular area that has been well researched; the challenge of water demand reduction will require accurate measurements to confirm the effectiveness of water reduction programs as more effort will be needed to achieve smaller water savings. The ultimate use of residential water demand analysis will determine their most appropriate form: for most utility companies and water resource management, the model will need to be flexible enough to match their needs but simple enough to execute with a reasonable degree of accuracy. New technologies will continue to improve residential water demand analysis, along with forecasts supporting more sustainable water resources and effective infrastructure management.

To help address gaps in the knowledge base that currently exist within the drinking water industry and research communities, research partnership that are aligned with industry concerns is recommended. Researchers and industry representatives should work closely together on real business issues by sharing their working framework, which will bring a new perspective on water industry challenges and solutions. Synergistic considerations that results from this type of collaborations will constitute 'value-added' to overall water utility process, which can be passed-on to a variety of stakeholders and constituents (Keck & Lee 2015).

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