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FACTORS INFLUENCING RESIDENTIAL WATER DEMAND: A REVIEW OF THE LITERATURE

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1. Introduction

A clear understanding of the drivers of residential water demand is essential if water managers wish to craft effective demand management policies. Since water is used as both a good for final consumption as well as an input to various activities (e.g. landscaping, washing clothes), analysts have approached estimating/forecasting water demand in two ways. The first, a "water requirements approach," attempts to estimate the quantity of water needed for a variety of activities consistent with an "average" household or individual. This figure, usually in terms of gallons per capita per day (GPCD) is then multiplied by forecasted population to predict future water demand. One flaw in this approach is that it does not allow for changes in consumer behavior in response to external influences such as changes in price, weather, or economic events (Nieswiadomy, 1992). The second, an "economics approach", attempts to model demand for water as a behavioral phenomenon. Household demand for water is modeled as a final good for consumption similar to that of any other good.[1] The decision to consume more or less is based on a variety of factors including price, weather, income, and so on.

Traditionally, researchers using the "economics approach" have relied on regression analysis as the primary tool for estimating household water demand. An equation relating total consumption to multiple demand-related variables is estimated. This approach allows researchers to isolate the effect of, for example, a change in price on quantity demanded, while controlling for other variables that factor into the consumer's decision process. These estimates then serve as the focal point of forecasts or scenario analysis (e.g. what effect will drier summers have on total demand) aimed at determining the potential effectiveness of various demand management policies.

The extensive literature on urban water demand discusses two primary categories of variables that drive demand: those that are controlled by water utilities and those that influence demand but are not directly utility controlled (e.g., *see* Gegax et al., 1998). Utility-controlled variables include the price of water, rate structures, and non-price voluntary and mandatory conservation programs such as outdoor watering restrictions, public education, and rebates. Non-utility controlled or "environmental variables" include weather and climate, socioeconomic factors such as household income and size, and characteristics of homes such as lot size and use of water efficient technologies. This review surveys the relevant literature regarding each of these factors.

2. Utility-controlled Factors Influencing Water Demand

Historically, most of the water demand literature has focused on price because of its role as a short and long-term demand management tool. The following section provides an overview of past attempts to identify the role that the price of water plays in

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[1] For a more detailed, yet still introductory, review of the theory behind these two approaches readers are referred to chapter two in Bauman et al. (1998).

the consumer's decision process, beginning with a brief description of the way water is priced throughout much of the United States.

2.01 The Role of Price in Determining Demand

As with many publicly provided goods, the price paid by individual households is not based on a series of market outcomes (e.g. the interaction of supply and demand). Rather, the rates, as well as the rate structures themselves, are often determined by the water provider.[2] This has resulted in the use of a wide variety of pricing schemes as utilities attempt to generate a stable stream of revenue while simultaneously promoting conservation and the equitable allocation of water among households.

Households typically pay a fixed service charge in addition to a per unit cost. Within the United States, there are three predominant rate structures used to price water: the uniform, increasing block rate, and decreasing block rate. Households facing a uniform rate structure pay the same marginal price for all units consumed. Households facing an increasing (decreasing) block rate structure face a constant price over the first units consumed, but pay a higher (lower) amount over the next units.

Increasing block rate structures have become increasingly popular because of their ability to promote conservation among individual water users. Evidence of this is provided by Cavanagh et al. (2002) who reported that between 1991 and 1997, among those surveyed, the number of utilities utilizing an increasing block rate to price water nearly doubled.[3] For this reason, much of the recent literature on the demand for water has focused on the impact of increasing block rates on demand.

(a) Approaches to Estimating the Effects of a Change in Price on Quantity Demanded

Of great interest to water managers is the effect that a change in price will have on quantity demanded. Absent an understanding of how consumers respond to price, policy makers must rely on trial and error to achieve revenue and conservation goals established by the utility (Brookshire et al., 2002). As a result, price elasticity of demand is typically the variable of interest; serving as one measure of the responsiveness of consumers to changes in price. Mathematically, price elasticity (P.E.) of demand is defined as follows:

$$P.E. = \frac{\%\, change\, in\, quantity\, demand}{\%\, change\, in\, price}$$

Estimating price elasticity of demand under traditional pricing schemes such as uniform rate structures is relatively straightforward. However, this task becomes more

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[2] Many have argued that, throughout the West, this has resulted in a divergence between the true social value of water and the price that most households pay (Brookshire et al., 2002).

[3] Along Colorado's Front Range nearly 90% of the utilities use some form of increasing block rate structure. EES (2004).

difficult when more complex rate structures (e.g. increasing and decreasing block rate structures) are employed. After more than fifty years of research, there is still little consensus as to how to estimate consumer demand under such rate structures (Arbués et al., 2003). Pint (1999: 249) summarized the state of the water demand literature as follows: “Generally speaking, water demand studies differ mainly in the type of data used [e.g. aggregate or household level] and the treatment of the price variable.”

(b) Which Price?

Contrary to what they face under uniform pricing, households facing block rate pricing pay a different price, both marginal and average, depending on the quantity of water they consume. This creates two potential problems. First, traditional economic theory focuses on marginal price as the sole price variable driving consumer demand. However, under block rate pricing structures, two consumers may face the same marginal price but different average prices regardless of whether there are fixed costs. This raises the question of which price should be used when estimating demand.

Second, embedded in consumers’ choice of how much they wish to consume is a choice concerning the price they wish to pay. That is, unlike uniform rate structures where consumers pay the same per unit amount regardless of the quantity they consume, under block rate structures consumers simultaneously choose both the quantity they wish to consume and the price they pay. Statistically, ignoring this issue may result in biased estimates of the price elasticity of demand.[4]

Many early water demand studies ignored the presence of block rates altogether, using the average price of water as the sole indicator of price (Billings and Agthe, 1980). However, as noted by Howe and Linaweaver (1967), such an approach ignores (a) the role that marginal prices play in determining consumer demand[5] and (b) that a change in the marginal price of a particular block may result in a reduction in quantity demanded yet result in little to no change in the average price paid.

Howe and Linaweaver (1967) argued that, to the extent that consumers equate marginal costs with marginal benefits, marginal price should be used to reflect this aspect of their decision process.[6] However, Taylor (1975) and Nordin (1976) noted that including only marginal price would ignore the “income effect” associated with the block rate structure. That is, households consuming in higher blocks pay a different per unit cost for units consumed in earlier blocks. For these customers, marginal price alone does not reflect differences in the price paid for each subsequent unit. In their work on household demand for electricity, they suggested that a “difference term” be included to account for the difference in total cost paid by the household given the rate structure they faced versus the total cost that would be paid by the household if they faced a constant

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[4] For a more detailed discussion of both issues see Bachrach and Vaughan (1994).

[5] Economic theory suggests that consumers equate marginal costs with marginal benefits when deciding how much to consume

[6] Their price elasticity estimates ranged from -.21 to -1.57 depending on geographic location and season of use.

marginal price across all units consumed. Billings and Agthe (1980) were the first to include both marginal price and a difference variable when estimating demand for water.[7] In theory, the impact of a change in the difference variable should equal that of a change in income. However, previous attempts to test this hypothesis have been unsuccessful. Arbués et al. (2003: Table 2 at 87) provides a summary of coefficient estimates for both difference and income variables from previous studies that illustrate this point.

There are two theories as to why this might occur. The first centers on whether or not consumers have enough information about their rate structure and consumption amounts to incorporate the full rate structure into their decision process (Nieswiadomy and Molina 1989). (This issue is discussed more fully below.) The second is based on the argument that the inclusion of a difference term alone does not correctly account for the changes in price across blocks, specifically, the endogeneity problem created by the simultaneous choice of price and quantity. Early attempts to resolve this problem modeled demand in a manner consistent with Taylor (1975) and Nordin (1976), but employed statistical techniques such as two-stage least squares or instrumental variables to account for possible endogeneity.[8]

More recently, Hewitt and Hanemann (1995) developed and applied a discrete-continuous choice model of consumer behavior to address this problem more formally. In their approach, the choice of how much water to consume is modeled as conditional on, and separate from, the decision of the block in which to consume.[9] This work represents a significant advancement in the development of a behavioral model under block rate structures.[10] However, it is computationally intensive and requires data at the household level which is often not available.[11] As a result few studies have utilized this approach (exceptions include Pint (1999) and Cavanagh et al. (2002)).

(c) Empirical Estimates of Price Elasticity

Despite the ongoing debate over the appropriate statistical techniques to be used, most studies have found that (1) residential water consumers respond to changes in price and

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[7] Their price elasticity estimates ranged from -.267 to -.61 depending on the type of functional form chosen (log v. linear) and the range of prices considered.

[8] For a comprehensive list of studies which have employed these techniques and the resulting elasticity estimates, readers are referred to Table 1 in Arbués (2003: 86-87).

[9] This approach is consistent with Taylor's (1975) observation that marginal price "governs behavior while the consumer is in that block, but it does not, in and of itself, determine why he consumes in that block as opposed to some other block."

[10] Hewitt and Hanemann (1995) obtained estimates of price elasticity that ranged from -1.12 to -1.63; considerably higher than most other studies. They suggested that these estimates were high in part because the study relied upon consumption data from June through August. Subsequent applications of this approach have generated estimates more in line with those found throughout the rest of the literature (e.g., *see* Cavanagh et al., 2002).

[11] Although complicated, the approach taken by Hewitt and Hanemann (1995) is especially attractive because it generalizes to both the case of increasing and decreasing block rate structures.

(2) demand for water is inelastic (i.e. its absolute value is less than one and significant).[12] That is, given a 10 percent increase in price, utility managers can expect total residential demand to decrease by less than 10 percent. Beyond these two points there is still considerable disagreement, much of which stems from the variety of complex pricing schemes employed by water managers and how to properly account for them in the analysis. In 15 studies reviewed by Brookshire et al. (2002), price elasticity ranged from -.11 to -1.588 with an average of -.49. By comparison, in a review of 24 journal articles, Espey et al. (1997) found that 75% of the price elasticity estimates reported ranged between -.02 and -.75. Both of these ranges are consistent with similar lists compiled by Bauman et al. (1998: Table 2-5, at 67); Brookshire et al. (2002: Table 1, at 880); and Arbués et al. (2003: Table 1, at 86), all of which provide comprehensive lists detailing past estimates of price elasticity found in the literature.

Evidence suggests that, within this range, the price responsiveness of consumers differs greatly depending on the time of year, geographic location, and socio-economic characteristics of consumers. That is, there are numerous economic, demographic, and climatic variables which not only directly influence demand for water, but also influence the price elasticity of demand for a given household.

(d) Differences in Price Elasticity by Season

Seasonal shifts in residential demand are common among most users located throughout the Southwest. These differences are typically attributed to outdoor demands for irrigation purposes that primarily occur during the spring and summer months. To the extent that outdoor uses are more responsive to price (because of the lower marginal value associated with their use) than indoor uses, then one would expect demand to be more price elastic during the summer months. Howe and Linaweaver (1967), Morris and Jones (1980), and Boland et al. (1990) all report price elasticity estimates that are 5-10 times higher during summer months as compared with those obtained for winter.[13]

(e) Differences in Price Elasticity by Geographic Location

Research also shows frequently significant differences in price elasticity between U.S. regions and cities, although the reasons for these differences are often unobserved and thus difficult to determine. For example, Nieswiadomy (1992), using data from a survey of 430 water utilities throughout the United States, found that residential users located in the southern and western United States were more than twice as responsive to changes in price than residents throughout the rest of the United States. Moreover, Renwick and Green (2000) estimated price elasticity for residents of Santa Barbara, California to be nearly three times those estimated for residents of nearby Goleta, California. Their findings are consistent with Cavanagh et al. (2002) who find significant differences in

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[12] Renwick and Green (2000) argue that this is consistent with what we would expect from economic theory. This is because water is a small portion of one's income, has relatively few substitutes, and serves as an input to many daily activities such as bathing.

[13] As reported in Bauman et al. (1998).

elasticity estimates across cities, even when using individual household level data controlling for factors such as household size and income.

(f) Differences in Price Elasticity Due to Social/Economic Characteristics

In addition to geographic differences in price responsiveness, it is highly likely that consumers within a particular region or city will respond differently to changes in price due to factors such as income and other household characteristics. Evidence of this is provided by Renwick and Green (2000) who found that low income households (i.e. annual income less than $20,000) were more than 5 times more responsive to price changes as households with income greater than $100,000 per year. The impact of income on water demand will be discussed in greater detail below.

(g) The Effect of Price Structure on Demand

In addition to differences in household characteristics, Cavanagh et al. (2002) suggest that consumer responsiveness to changes in price is likely influenced by the type of rate structure used. In their study, households facing a two-tier increasing block rate were 5 times more sensitive to changes in price than households facing a uniform rate structure.[14] In a subsequent write-up of this work, Olmstead et al. (2003:25) conclude that “price structure may be an important and cost-effective alternative to command-and-control approaches, and possibly a more effective alternative, in terms of its ability to reduce water consumption, than increases in the magnitude of marginal price, itself.”

Along these lines price elasticity of demand has also been shown to be sensitive to frequency with which customers are billed. Stevens et al. (1992) and Kulshreshtha (1996) both suggest that the effectiveness of price as a demand management tool may be highly dependent on the characteristics of the rate structures and billing process utilized.

(h) Type of Data; Individual vs. Aggregate Water Use

Outside of questions pertaining to how to estimate demand, the appropriate type of data (e.g. utility-wide vs. consumer level; single observation versus multiple observations across time) has been one of the larger issues discussed in the literature (Brookshire et al., 2002). While it is widely recognized that multiple observations of individual households across time are preferred, few studies have been able to utilize this type of data because it is often too costly to acquire or simply not available.[15] Commenting solely on the level of data used, Hewitt and Haneman (1995: 2) concluded that, of the literature they reviewed,

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[14] It is important to note that “due to differences in mean values of important independent variables” (pg. 27), they are unable to rule out selection bias or other factors as the cause of this difference between consumers.

[15] “In theory, the estimation of residential water demand function within a micro setting using household level data is the preferred approach. However, attempts at the micro level are rather few, since they require a great volume of information” (Arbués et al., 2003: 89).

"fewer than half the studies used disaggregate household level data appropriate to a model of individual behavior…"

Due to the lack of available data, many studies are forced to rely on annual, aggregate, city-wide (or utility-wide) data which fail to account for heterogeneity of individual households. This becomes more important under increasing block rate structures, where households face a different price depending on their level of consumption (Schefter and David, 1985). Under block rate structures consumers whose last unit of consumption occurs in the first block will respond differently to price changes in that block than consumers located in subsequent blocks (Goemans, 2006). When only aggregate data is available, failing to account for the distribution of users consuming in each block can produce biased estimates of price elasticity. Martinez-Espineira (2002) attempted to correct for this by using the proportion of users per block to weight aggregate consumption. However, the author was unable to demonstrate a significant difference between the price elasticity estimates generated using this approach and that consistent with past studies.

Ideally, researchers would be able to study the behavior of individual households across time. Panel data, i.e. data sets that contain multiple observations on individual households, have been used by Nieswiadomy (1992), Moncur (1987), and Niewsadomy and Molina (1989) to name a few. Few studies have employed more advanced panel data techniques, e.g. utilizing fixed effects or random coefficients. Techniques such as these allow the researcher to control for unobserved differences across individuals within the data set. Examples include Pint (1999) and Martinez-Espineira and Nauges (2004); both obtained price elasticity estimates within the range of past studies.

(i) Remaining Issues Pertaining to the Effects of Price on Demand

Despite general consensus over the range that price elasticity likely falls in, disagreement still exists in three areas. First, it is unclear whether consumers are actually aware of the price and rate structures they face. Second, there is uncertainty as to whether the range of prices reflected in past studies is sufficient to predict the response of consumers outside this range. Lastly, relatively little is known about the use of non-price demand management tools together with pricing policies. Each of these three issues is discussed in more detail below.

(i) Consumer Awareness of Price

All of the studies presented above make explicit assumptions involving how much information consumers have about the prices they pay for water and how they incorporate that information into their decision process. Many have argued that "most consumers will not devote much time or effort to study the structure or change in intra-marginal rates because of information costs" (Arbués et al. 2003: 84). Jordan (1999) references a survey of 400 Georgia consumers in 1992. Of those surveyed, slightly more than 60 percent were aware of what they paid on average; however, only twelve people indicated that they knew their water rate (and eight were wrong).

The extent to which consumers are aware of, comprehend, and incorporate the often complex billing structures into their decision process is not well known. The importance of this issue lies in both determining the appropriate statistical techniques to be used, as well as the ability of utilities to predict the short and long-term response of consumers to changes in price.

From a management perspective, responsiveness to changes in both the level and/or shape of a rate structure (e.g. change in block 1 versus change in block 2) are likely to differ depending on awareness of the price changes and rate structure itself. When reflecting on the City of Tucson's attempt to reduce per capita demands during the 1970s, Martin et al. (1984: 66, as quoted in Nieswiadomy, 1992:610) suggested "Major decreases in water use per capita occur only where a major price increase is accompanied by major public awareness of the action surrounding the passage of the increased price schedule."`

From an econometric perspective, how consumers incorporate the price information they have into their decision process is important in terms of correctly modeling their responsiveness to changes in price. Whereas Hewitt and Hanemann (1995) argue that this issue is not important as long as actual behavior is consistent with that of a well informed consumer, there is evidence to support the contention that consumers don't behave this way. Billings and Agthe (1980) recognized the possibility that consumers may not fully understand all of the nuances of their water bill. They questioned whether or not customers in their study were likely to be aware of the method of calculating sewer charges (they were calculated using a complicated formula based on consumption during December, January, and February). To test whether or not consumers were aware of, and respond to, the marginal sewer costs they included an "implicit marginal sewer charge" as a separate price variable. They found the coefficient on this variable to be insignificant, suggesting that customers are unaware of how sewer chargers are calculated, instead responding only to the billed sewer portion of their bill as a lump sum.

If consumers are not aware of price then which price do they respond to? The question of which price consumers respond to has been the subject of many water and electricity demand articles. Shin (1985) developed a now widely applied test to identify whether consumers responded to the average or marginal price. The application of this approach to water demand estimation has suggested, for the most part, that consumers are more likely to focus on average price rather than marginal price (e.g., see Niewsiadony 1992). Niewsiadony's (1992) analysis (using Shin's approach) of water demand across regions suggested that customer were more likely to respond to average price regardless of which region they were located in.

More recently, Carter and Milon (2005) combine survey data with household water use data from three Florida water utilities. As part of the survey, households were asked whether they knew the marginal and averages prices they faced. Only 6 percent of those surveyed reported that they knew the price. Controlling for whether households indicated they knew the price of water, their results suggest that (a) households facing increasing block rate structures are less likely to know the price of water, and (b) consumers who indicated that they knew the price of water were two to five times more responsive to changes in price and also, on average, used more water.

(ii) The range of price changes studied has been relatively small

As long as price variation is small and predictions are made within a similar price range, predicted responses should be reasonably close regardless of the true functional form. However, if the range of prices under consideration falls outside of the range of prices reflected in previous studies or if the functional forms are not consistent with consumer behavior, the applicability of past results may be questionable.

Historically, the price of water has varied little in real terms (Brookshire et al., 2002). As a result the range of prices considered in past studies has been relatively small (Pint, 1999). Moreover, because of a lack of data few studies have been able to study the effects of short-term price jumps such as those implemented during periods of drought. Because there is evidence that price elasticity of demand for water is not constant, elasticity estimates at low prices could differ substantially from those at high prices. That is, currently available elasticity estimates may not reflect actual consumer responsiveness outside of the range of prices considered in previous studies (Krause et al., 2003).

Pint (1999) is one exception. She uses data from California before and during the 1987-1992 drought. Because of a switch to increasing block rates, her data set included price increases exceeding 400 percent for water that was sold in the highest block. However, price increases were still relatively small for water sold in the first few blocks. Her estimates of price elasticity were consistent with past studies.[16] Lacking the data necessary to explore responsiveness over an appropriate range of prices researchers increasingly are attempting to capture the nonlinearity in price responsiveness by using different function forms (Gaudin et al., 2001) or by conducting experiments (Krause et al., 2003).

(iii) Interaction between price and non-price policy changes.

When considering the effect of pricing policies on residential demand, it is important to consider any non-price measures that may also exist. Two issues are particularly important. First, to the extent that non-price policies are implemented simultaneously with price changes, failure to account for the presence of non-price policies will likely produce inaccurate estimates of price elasticity, attributing the affects of the non-price policies to the changes in price (Renwick and Green, 2000). Second, as was suggested by Moncur (1987), it likely that a synergistic relationship exists between the two policies—i.e., consumers are likely to respond differently to changes in price that occur when other non-price policies such as mandatory restrictions are in place (Howe

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[16] It should be noted that these price increases were largely associated with a change in the rate structure, rather than an increase in price for all units consumed.

and Goemans, 2002). Again, failing to account for this will produce inaccurate estimates of price elasticity.

Although frequently used in conjunction with each other, both price and non-price demand management tools have been analyzed in only a few studies; examples include Nieswiadony (1992) and Renwick and Archibald (1998). However, even these studies failed to account for the potential *interaction* of price and non-price policies in their analysis. Economic theory suggests that the introduction of a constraint on water use should impact the responsiveness of consumers to changes in price (Howe and Goemans, 2002). Such a relationship was originally suggested by Moncur (1987) who hypothesized that price changes made during periods when voluntary water-use restrictions were in place would be more effective. Despite this assertion, he was unable to test for this effect because of limitations imposed by the data set. To test for this effect, Michelson et al. (1999) included a "price-non-price conservation program interaction variable"; however, this variable was statistically insignificant in their study. They utilized as a conservation term the number of conservation programs in each of the seven studies they examined, but the term did not distinguish between the different types of programs

2.02 Non-Price Mechanisms

Due perhaps to political opposition, equity concerns, and legal limitations, water utilities may be reluctant to use price to allocate scarce supplies of water. Instead they often implement programs such as voluntary and mandatory water use restrictions or public education that try to influence consumers to demand less water for the same price, or alternatively they institute programs that try to change technology/infrastructure by, for example, offering rebates for purchases of water efficient appliances and irrigation technologies (e.g., see Cavanagh et al., 2002; Gegax et al., 1998). However, evidence of the effectiveness of these programs has been mixed and, as Cavanagh and others have pointed out, non-price programs may end up costing consumers more after program costs are factored in. Further, some have criticized the efficiency of mandating reductions in specific water uses through outdoor watering restrictions, rather than simply allowing households to select the most cost-effective ways to reduce water use. As Billings and Day (1989: 59) note: "Rate structure…has the advantage of avoiding the costs of overt regulation, restrictions, and policing while retaining a greater degree of individual freedom of choice for water customers."

(a) Non-price programs in general.

Michelsen et al. (1999) examined non-price conservation programs in 7 cities over an 11-year period. The types of programs included public information; school educational programs; retrofit programs; permanent ordinances and regulations to, for example, require installation of water saving appliances; and temporary ordinances and regulations. They used a cross sectional, monthly time series residential water demand model to estimate the effectiveness of non-price conservation programs, taking into account changes in demand from price, precipitation, temperature, income, city size, use over time, drought, and number of conservation programs. Their methodology assumed that all programs and levels of commitment were identical since there were insufficient data to separate individual programs. They found the effectiveness of conservation programs have pronounced but declining marginal effects; that is, the per program effectiveness declines as the total number of programs increases. They also found the effectiveness of programs was not uniform across time. Reductions in use ranged from 1.1 to 4% per program.

Using the same model and database as Michelson et al. (1999), Gegax et al. (1998) found non-price programs had a significant, negative influence on water use, reducing it by an average of 2.9% per program. However, they were unable to determine the effectiveness of individual specific programs. The authors conclude that non-price conservation programs are effective if the city achieves a critical mass of programs. The effectiveness of conservation programs in cities with a small number of programs or relatively new experience with conservation is less and may even be zero. These results appear inconsistent with Michelson et al's finding that cities that have implemented the fewest number of programs had the relatively largest per program effect.

As suggested in the previous section, Michelsen et al. (1999) tested Moncur's (1987) idea that there may be a synergistic relationship or effect between non-price conservation programs and price elasticity but found a statistically insignificant interaction or cross effect between price and non-price conservation programs. They note that previous studies of the effects of non-price conservation programs have overestimated the effects of such programs by using a "before and after" comparison which fails to account for the fact that utilities often implement multiple non-price programs at the same time, and such changes are often associated with other deviations from the norm such as changes in price and drought. Gegax et al. (1998) also examined this issue; estimates from their model of water use in Los Angeles suggest that half the savings were due to price increases and the other half to an increase in the number of non-price conservation programs.

(b) Voluntary and mandatory restrictions.

Voluntary restrictions generally involve requests that customers limit their outdoor watering to a particular schedule (i.e. every other day, every third day, two days a week, etc.) but without any enforcement mechanism. Mandatory restrictions, on the other hand, require that customers follow a watering schedule and impose penalties, usually in the form of fines, for known violations. Mandatory restrictions may also involve quantity limitations.

The literature comparing the effectiveness of voluntary and mandatory outdoor water use restrictions implemented by the same or nearby water utilities has generally concluded that mandatory outdoor water restrictions are more effective than voluntary restrictions, which often produce little savings. One of the few exceptions is provided in

Shaw et al.'s (1992) finding that during the 1990-91 drought, voluntary restrictions reduced summer water use in San Diego by 27% (though this was less than Los Angeles' 36% reduction from mandatory restrictions). In most other studies, as shown below, voluntary restrictions had much less of an impact on water consumption. However, since each of the programs is somewhat different, the percentage reductions indicated are specific to that set of restrictions.

Kenney et al. (2004), applying both a simple "before and after" comparison as well as an "expected use" model including weather data, found mandatory outdoor watering restriction savings reduced municipal demand between 13% to 56%, depending on the Colorado Front Range city studied, the severity of the restrictions, and the method of calculating savings. Voluntary restrictions resulted in anywhere from a 12% savings to a 7% increase in use, depending on calculation method.[17] Using the "expected use" calculation produced additional savings over the "before and after" comparison of between 1% and 8%.

Lee (1981) studied the drought response of 12 Iowa communities in 1977, all of which used voluntary restrictions, and with four later adopting mandatory policies. Water conservation policy-makers rated the mandatory policies more effective than the voluntary policies. Using a multiple regression model to predict water demand under normal conditions and comparing actual and predicted demand, communities with mandatory policies achieved greater savings than those with voluntary policies. However, communities with voluntary policies that were located near communities with acute water shortages also achieved significant savings. Research by Lee and Warren (1981) also found mandatory programs to be most effective.

Narayanan et al. (1985) examined effects of maximum use restrictions and restrictions on times of outdoor watering in 33 Utah communities during the 1976-77 drought. Cities employed both voluntary and mandatory time restrictions, but the analysis did not distinguish between the two since the cities with mandatory restrictions did not enforce them. Quantity restrictions ranged from 6,000 to 36,000 gallons per month per connection. Time restrictions were shown to be effective in reducing demand, especially for systems with higher use levels and fewer people per connection. Voluntary restrictions sometimes resulted in an increase in water use, particularly for systems with smaller use levels and a greater number of people per connection. The authors theorized that voluntary restrictions may cause consumers to over-water since they expect stronger restrictions later in the season.

Renwick and Green (2000), applying an econometric model of residential water demand to monthly water use data from 8 California water agencies between 1989 and 1996 (which included a drought period), found mandatory restrictions such as prohibitions on washing sidewalks and driveways or bans on landscape watering during

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[17] The authors note the one city with a 7% increase had only 12 days of voluntary restrictions, which may account for the result. But other authors who have observed increases during voluntary restriction periods theorize that consumers overuse water during that time in anticipation of the mandatory restrictions that are likely to follow.

peak hours, reduced average demand by 29%; rationing programs that allocate a fixed quantity of water to households reduced average demand by 19%; and, overall, mandatory restrictions reduced demand substantially more than voluntary measures.

Shaw and Maidment (1987) examined the impact of both a voluntary and mandatory restriction program in Austin, Texas, 1984-85. The mandatory program allowed outdoor watering only once every five days within a specified time period with fines of up to $200 for noncompliance, while the voluntary program asked for compliance with the schedule but without any enforcement. Using intervention analysis, a stochastic modeling technique that quantifies changes in a time series due to an external intervention, they found that, after accounting for departures from normal weather, mandatory restrictions were almost five times more effective in reducing water use than voluntary restrictions. Similar findings were made by the authors in their study of drought response in Corpus Christi, Texas, in 1984 (Shaw and Maidment, 1988). They found voluntary restrictions had little or no effect on daily water use, whereas first stage mandatory restrictions resulted in savings of 31% from “expected use.” More severe restrictions which included a total ban on lawn watering and strict limits on the amount of water allocated to customers saved 39%. Overall savings from mandatory restrictions was about 33% from expected use. Voluntary restrictions had a negligible effect.

Anderson et al. (1980), applying three multiple regression models to municipal level data during a drought year that included rainfall and temperature as variables, found mandatory twice a week outdoor watering restrictions reduced water use by 41% below normal. However, based on an analysis of evapotranspiration data it was estimated that over half of this savings was due to abnormally wet weather. Under normal weather conditions a reduction of 19.7% from restrictions would be expected. The study did not compare the results of a voluntary restrictions program.

Renwick and Archibald (1998), applying an econometric model of household water demand which explicitly considered irrigation system technology in 2 California communities during a drought period, found a ban on virtually all landscape irrigation except hand irrigation and drip systems reduced average household water demand by 16%. A mandatory water allocation policy that gave each household a base allocation of 132 hundred cubic feet per year plus 55% of annual average usage above this amount reduced water demand by 28.2%; both policies caused greater reductions in homes with large landscaped areas. Again, no comparison with a voluntary restriction program was included.

Lee (1981) and Lee and Warren (1981) offer several reasons why residents may or may not cooperate with restrictions: First, they respond if the credibility of local government with regard to drought information is high. Credibility can be enhanced by mass media cooperation and proximity to communities with severe shortages. Second, fear of running out of water encourages cooperation. Finally, a sense of community spirit is a consideration. Credibility of water shortage information provided by local officials and fear of running out of water are more important determinants of whether residents conserve than penalties associated with mandatory restrictions. Demographic characteristics may also play a role in whether residents respond to restrictions. de Oliver (1999) found that Anglo Republicans with higher incomes and higher education levels responded less to voluntary conservation measures than non-Anglo Democrats with lower incomes and educational levels. However, these distinctions did not apply once mandatory restrictions were implemented.

A word of caution is in order in interpreting these studies. Estimating the exact range of water savings can be difficult; as Little and Moreau (1991) note, the effectiveness of restrictions can be largely influenced by research assumptions and methodological approaches. The majority of the relevant studies use regression-based approaches with dummy variables to estimate conservation savings typically at a citywide level and over long (weekly or monthly) time scales, rather than an approach that models daily changes in demand, or at the level of individual consumers. Little and Moreau (1991) are among the authors advocating greater use of daily demand models to accurately estimate what demand would have been absent conservation, including meteorological (weather) data.

(c) Public information campaigns

Public information campaigns urging customers to conserve water often arise in conjunction with drought, and are frequently used to avert or delay more drastic measures such as mandatory restrictions or price increases. Some utilities are also using these campaigns on a long-term basis to instill a conservation ethic. Supporters claim they are effective in saving water and are more politically acceptable than other more restrictive measures. Critics charge that any savings from public information campaigns are small and likely to be temporary, and that other measures are more effective. Some of the voluntary restrictions programs described above include a public information component, so it is somewhat artificial to separate this discussion from the discussion of voluntary restrictions.

Syme et al. (2000), in a review of the literature evaluating the effectiveness of public education campaigns to promote voluntary water conservation, conclude that education campaigns can result in up to 25% water savings in short-term or crisis situations but their long-term effectiveness has not yet been shown. Further, the studies reviewed found that written material, alone, is unlikely to be effective.

Mercer and Morgan (1980), cited in Syme et al. (2000:544-545), used expenditures on publicity as a variable in a regression equation. They found an elasticity of publicity of -0.04 (i.e. a 10% increase in public education expenditures produced a decrease in water use of 0.4%), compared to a price elasticity of -0.36. Billings and Day (1989), found that publicity about water problems, measured by the number of articles appearing in the leading area newspaper, had an elasticity of -0.05 (i.e. a 10% increase in the amount of publicity produced a 0.5% reduction in use). The effect of publicity was found to exist only as long as the publicity continued (that is, there was no lagged effect).

Nieswiadomy (1992) found public education reduced water demand in the West, perhaps due to heightened awareness of water scarcity in that part of the country. Renwick and Green (2000) found public information campaigns reduced average household demand by 8%. And as noted earlier, Shaw et al. (1992) found that San Diego's voluntary conservation program—which relied exclusively on extensive education, advertising, and publicity campaigns—resulted in an annual reduction in use of 22%.

Wang et al. (1999), cited in Syme et al. (2000:546), comparing the relative effectiveness of three strategies, found that price was the strongest predictor of water use savings, followed by participation in the water savings device program with an information campaign only marginally effective for one year. Bruvold (1979), cited in Syme et al. (2000:547), comparing effectiveness of water conservation campaigns using only persuasion with those with a variety of penalties and regulations, found the persuasive programs reduced summer per capita use by 33% from the previous summer, while programs with penalties and regulations reduced consumption 53-63%. Watson et al. (1999), comparing the effectiveness of an education strategy using a large-scale television advertising campaign, and providing materials and curriculum support for schools, with price increases to encourage water conservation, found that the educational strategy was more successful in improving water conservation than the price strategy.

One of the problems in identifying the effectiveness of public information campaigns is that they are frequently implemented in conjunction with other demand management strategies such as outdoor use restrictions and price increases, and it is difficult to separate out the effect of each strategy. This problem was discussed in the Michelson et al. (1999) study described above.

To summarize, the studies of mandatory restriction programs found savings anywhere from 13 to 63% while voluntary programs (including public information campaigns) produced anywhere from a net increase in water use of 7% to savings of 33%.

(d) Retrofits

In an effort to reduce demand, many water utilities have offered financial incentives to persuade customers to purchase water efficient technologies such as low flow toilets and rain sensors to shut off automatic sprinkler systems. Many studies have demonstrated significant water savings resulting from toilet retrofit programs (e.g., *see* Bamezai, 1996; Chesnutt et al., 1992; and Mayer et al., 1999). Additionally, many cities also offer water conservation kits that may include a variety of devices and information. These may be drought motivated, or may be part of long-term conservation programs. Renwick and Green (2000) found distribution of free retrofit kits with a low flow showerhead, tank displacement devices, and dye tablets for leak detection reduced average household demand by 9%. Palmini and Shelton (1982) found that a retrofit program undertaken to forestall long-term supply problems rather than in response to drought produced average annual savings of around 5,000 gallons per household receiving a kit, and approximately 7,400 gallons per home that installed one or more of the devices (since not all homes installed the devices). Renwick and Archibald (1998), using an econometric model of household water demand that explicitly incorporates technological change, found that increasing the number of low flow toilets by one decreases household demand by 10%, increasing the number of low flow showerheads by one decreases household demand by 8%, and adoption of water efficient irrigation technologies reduced average household demand by 11%; overall, households with large landscaped areas reduced total usage by 31% while those with smaller landscaped areas reduced use by 10%.

2.03 Other Issues

(a) Ongoing effectiveness of drought management programs

Several studies have found an ongoing effect from drought management programs even after a drought has ended. Gilbert et al. (1990) found that although drought conditions improved in year 2 of the East Bay Municipal Utility District’s 1987-88 drought management program, consumption still fell 33% in the residential customer class, well below the 19% reduction target. The authors note “the difficulty in modulating conservation to a specific level, especially after a program such as was invoked in [the previous year].” Shaw et al. (1992) found that water use reductions achieved through San Diego’s voluntary program persisted later in the year despite a return to wetter weather, and even exceeded reductions achieved by a nearby city with mandatory restrictions. Similarly, Shaw and Maidment (1988) found that the conservation effect continued the year after a mandatory restrictions program ended. They attributed most of the change to decreased use by large industrial users who made substantial capital purchases of water savings devices and equipment or altered manufacturing processes, resulting in a permanent decrease in base water use. This experience and a similar one in California suggested to researchers that stringent long-term conservation may “train water users, especially those in the industrial sector, to adjust their normal habits toward decreased consumption” (Shaw and Maidment, 1988: 77).

3. Environmental (Non-Utility Controlled) Factors Influencing Water Demand

3.01 Weather[18]

Previous attempts to model household demand for water have, in general, focused on characterizing the effects of various economic and policy variables, often including weather variables only to control for such factors rather than to understand the impact of climate on demand (Gutzler and Nims 2005). While scientists generally agree that weather-related variables may affect water demand, a consensus beyond this has yet to be reached. [19] Gutzler and Nims (2005:1778) characterize the state of the literature as follows, “Previous studies for other localities in the southwestern United States have reached surprisingly diverse and apparently contradictory conclusions about the impact of climatic variability on water demand.”

Much of the disagreement appears to center on two questions: (1) which weather-related variables do consumers actually respond to (e.g. temperature versus precipitation); (2) do households respond to changes in weather as continuous events or based on predetermined thresholds, i.e. do households respond to the amount it rains or simply that it rained? The following two sections address each of these areas.

(a) Variables of interest

The most common approach for considering the effect of climate conditions on water demand is to include some combination of temperature and precipitation variables in the regression equations.[20,21] In addition to temperature and precipitation, several studies included an evaporation-related variable. For example, net evapotranspiration (potential evapotranspiration minus actual rainfall) is commonly included to reflect the actual needs of plants. Studies utilizing this approach include Agthe and Billings (1986); Berry and Bonem (1974); Billings (1982); Billings and Agthe (1980); Morgan and Smolen (1976); Nieswiadomy and Molina (1988); and Wilson (1989). Both potential and net evapotranspiration indirectly account for changes in temperature and precipitation as well as other weather variables.[22]

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[18] Note that the research cited in this section focuses on western states or other semi-arid environments, like Colorado.

[19] Most studies of this type find “weather” to be significant in influencing demand. For examples see Agthe and Billings (1986), Al-Qunaibet and Johnston (1985), Billings (1982), Billings and Agthe (1980), Billings and Agthe (1998), Foster and Beattie (1979), Foster and Beattie (1981), Griffin and Chang (1990), Hewitt and Hannemann (1995), Nieswiadomy and Molina (1988), Piper (2003); and Stevens et al. (1992).

[20] Examples include Billings and Agthe (1998); Cochran and Cotton (1985); Gegax et. al. (1998); Gutzler and Nims (2005); Hansen and Narayanan (1981); Martinez-Espineira (2002); Miaou (1990); Michelson et. al. (1999); Nieswiadomy (1992); Piper (2003); and Stevens et. al. (1992).

[21] Only a few studies in this literature review accounted for the effects of precipitation (Foster and Beattie, 1979; Foster and Beattie, 1981; and Hewitt and Hannemann, 1995); conversely we did not come across any studies that only accounted for temperature.

[22] Likewise, only a few studies in this literature review utilized estimates of pan evaporation (Anderson et. al., 1980; Maidment and Parzen, 1984; Woodard and Horn, 1988). Pan evaporation involves an actual measurement of evaporation from a pan of water over a given time period.

In a similar vein, effective precipitation has also been used to reflect changes in the quantity of water "needed" for outdoor irrigation purposes. Bamezai (1997), in a study of landscape irrigators in southern California, defined effective precipitation as 50% of actual precipitation. By comparison, in a study of water demand throughout parts of New Mexico, Berry and Bonem (1974) assumed that 60% of rainfall was effective. Finally, Anderson et. al. (1980), in a study during a drought in northern Colorado, defined effective precipitation as daily precipitation between 0.1 and 0.6 inches in one model and in their second and third models they assumed that 40% of precipitation is used the first day, 40% the second day and 20% the last day.

Several studies have taken more complex approaches to modeling the effects of weather on demand for water. For example, Al-Qunaibet and Johnston (1985) created a humidity variable based on monthly mean temperature, monthly mean minutes of sunshine, and monthly mean wind speed. Bamezai (1997) created a weather index based on daily reference evapotranspiration, daily crop coefficient, daily precipitation, effective proportion of precipitation, and surplus effective rainfall carryover. The last variable was based on days when effective rainfall exceeds the evapotranspiration demand; the difference is carried over to the next day. These daily weather indices were then aggregated to monthly values because the customers were billed monthly.

As noted earlier, in addition to uncertainty over *which* weather variables consumers respond to, there is still uncertainty regarding *how* they respond to them. For example, Billings and Day (1989) used winter and summer rains as separate variables and a "high temperature" variable to examine the response of water use to temperatures above some critical level. Griffin and Chang (1990) created a climate index equal to the number of days without significant rainfall (< .25 inches) multiplied by the month's average temperature. By comparison Maidment and Miaou (1986) created a heat function by selecting weekly average values of detrended water use compared with corresponding average values of maximum air temperature. They selected data points such that there was no rain in the previous N days, which removed any effects of rainfall on water use. (The N days changed for each city in the study and by season.) Rhoades and Walski (1991) use separate regression equations for each month and transform the monthly rainfall totals into log for 8 months. They assumed that the first amounts of rainfall dramatically decrease outdoor watering, but as rain continues, its effect steadily decreases.

Another alternative modeling approach is to use nonlinear regression models. Bamezai (1997) captured a nonlinear weather response by constructing weather variables from daily deviations in weather indices. The weather indices were based on daily reference ET, daily crop coefficient, daily precipitation, effective proportion of precipitation, and surplus effective rainfall carryover. Surplus effective rainfall carryover was based on days in which effective precipitation exceeded the evapotranspiration demand; the difference was carried over to the next day. He found that a nonlinear response was preferred, but linear models with a time-varying response also were significant.

Maidment and Miaou (1986) and Miaou (1990) assumed that monthly water use can be separated into base (winter) use and seasonal (summer) use and that the relationship between climate and water demand may not be linear. Maidment and Miaou (1986) compared the use of linear and nonlinear regression equations for estimating the effects of climate variables on daily water demand in three cities each in three states (Texas, Florida, and Pennsylvania). They removed trends in base and peak use and the "long memory" seasonal fluctuations by subtracting the potential water use that would occur with average temperature and no precipitation for each day. They also removed weekly cycles. They look for the "short memory" component of demand, which is affected by the occurrence of rainfall and anomalous daily air temperatures. They conclude that the relationship between climate and water demand is nonlinear because the response of water use per unit change in temperature or precipitation depends on the magnitude of each weather event. In addition, they concluded that the effect of a precipitation event is "state-dependent" because it depends on the water use level immediately before the event. Similarly, Miaou (1990) separated the effects of temperature, precipitation in inches and rainy days per month. His regression equations identify thresholds beyond which excess rainfall or numbers of rainy days per month would not continue to affect water use in Austin, Texas. Each of these studies allowed for the possibility that consumer response to changes in weather is discontinuous and/or non-linear.

(b) Time scales for weather variables

Changes in weather can occur quickly; however, because water consumption is often observed at a monthly (i.e. billing period) or yearly time-step, most studies use climate variables that have been aggregated in monthly, seasonal, or annual time scales to evaluate the effect of changes in weather on water demand.[23]

In the semi arid and arid parts of the western U.S., outdoor irrigation in the summer months is a large portion of domestic water use. Therefore, the studies that rely on seasonal weather data tend to focus only on the summer months or the growing season with the assumption that weather does not affect water use in the winter because there is no outdoor irrigation. This approach has also been utilized by several studies that have used monthly or daily weather data. Examples include Anderson et al. (1980), Gutzler and Nims (2005), Hansen and Narayanan (1981), Hewitt and Hannemann (1995), Morgan and Smolen (1976), Nieswiadomy (1992), and Nieswiadomy and Molina (1988).

(c) Seasonal variability of water demand

Gutzler and Nims (2005) compared how seasonal and interannual fluctuations in

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[23] Examples that used monthly data include Agthe and Billings (1986); Al-Qunaibet and Johnston (1985) Cochran and Cotton (1985); Gegax et al. (1998). Examples utilizing seasonal data include Berry and Bonem (1974); Billings and Day (1989); Foster and Beattie (1979); Foster and Beattie (1981); and Wilson (1989).

climate affects water demand in Albuquerque, New Mexico. They used three different regression models with different dependent demand and independent climate variables. The first one evaluated the effect of climate variables on residential per capita demand anomalies for the summer season over two time periods. The climate variables were seasonal anomalies of average daily maximum temperature and daily precipitation rate. The second and third regressions evaluated the effect of climate variables on year-to-year demand changes. The second regression looked at actual demand anomalies from year to year and the third one looked at per capita demand anomalies. Both the second and third regressions used changes in climate variables (seasonal averages of temperature and precipitation) from year to year as the independent variables. In each of the three types of regressions, the authors examined the effect of each of the climate variables separately as well as together. They found that models evaluating the interannual change in demand explained double the variance that the models looking at seasonal demand anomalies explained. Gutzler and Nims concluded that climate affects long-term changes in water demand, rather than short-term seasonal changes.

(d) Key findings related to weather variables

Nearly all studies in this literature review that include weather variables found at least one weather variable to be a significant determinant of water demand (e.g., *see* Hansen and Narayanan, 1981; Morgan and Smolen, 1976; and Billings and Day, 1989). Precipitation, or quantity of rainfall, is often singled out as a more useful predictor than temperature. For example, Gutzler and Nims' (2005) study of Albuquerque, and Rhoades and Walski's (1991) study of Austin both found precipitation to be the most useful weather variable in explaining daily municipal water demand. Wilson (1989) did not look at temperature, but he found that moisture deficit[24] was more important than other variables (marginal price of water and market value of home) in determining average summer sprinkling demand per dwelling unit.

One of the most sophisticated studies examining weather and water demand was done by Maidment and Miaou (1986), who examined weekly municipal water use in three cities of three states – Texas, Florida, and Pennsylvania – and compared it to a heat function, a temperature function, and rainfall events. The results for Texas are likely illustrative for conditions throughout much of the West. Using their heat function (maximum air temperature with rainy days removed), the authors found that in Texas cities, water use rises when temperature reaches about 70 ^{o}F, and then rises sharper at about 90 ^{o}F. These results prove the nonlinearity of the heat function. Using their temperature function (daily maximum air temperature separated into summer months and the rest of the year), the authors found that in Texas the response from a hot day will decay such that each successive day has two-thirds the response of the previous one. Therefore, the effect of a high temperature one day will be felt for five days in the future. Also in Texas, the response of water demand to the temperature function was higher in the summer than in winter by a ratio of 2:1. Finally, the authors found that the sustained

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[24] Moisture deficit equals summer (June-Aug) evapotranspiration minus .06 summer precipitation.

effect of a rainfall event is two weeks, but the immediate drop in water use following a rainfall event is partly explained by the corresponding temperature drop, which occurs at the same time. In Texas, the decrease in seasonal water use one day after a rainfall is 38% of the previous day's use on average.

Another study of the weather component of water demand in two Arizona cities (Phoenix and Tucson) was conducted by Woodard and Horn (1988), who found that daily municipal water demand was significantly correlated to both pan evaporation and cooling degree days. Cooling degree days were more important for Tucson, probably because of the abundant use of evaporative coolers. Similar to Maidment and Miaou's (1986) findings, Woodward and Horn (1988) found that precipitation events decreased water demand from one day before the event to several days following. The reduction the day before is likely due to weather forecasts. Precipitation events explained about 27% of the total variation in water demand data, and events that lasted several days had less of an effect on water demand than distinct rainfall events that had dry days in between them. Monsoon precipitation in the summer months (May - Sept) had much more of an effect on water demand than winter precipitation, probably due to increased water demand for outdoor use in the summer and not in the winter. In addition, the number of monsoon precipitation events was a better predictor than the amount of rain that fell with each event.

Anderson et al.'s (1980) study conducted during a drought in Colorado is also notable in that it explicitly linked observed demand reductions during drought to both management actions (watering restrictions) and short-term weather variables (daily precipitation, temperature and pan evaporation) over the same period. They concluded that over half the observed water savings were actually the result of favorable weather conditions.

Despite the vast literature linking weather to water demand, it is worth noting that several studies have failed to show a significant relationship. However, in most cases, it appears likely that this reflects data limitations and/or methodological shortcomings, most commonly, by not separating out residential water users and/or differentiating seasonal water use. (e.g., *see* Berry and Bonem, 1974; Cochran and Cotton, 1985; Gegax et al., 1998; Maidment and Parzen, 1984; Miaou, 1990; Michelsen et al., 1999; and Nieswiadomy, 1992).[25]

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[25] Berry and Bonem's (1974) study of municipal water use in several New Mexico cities did not separate out residential water use or water use during spring and summer months from the rest of the year. They found that aggregate spring and summer potential evapotranspiration and total spring and summer rainfall were not significant in a regression of daily municipal water use. Gegax et. al. (1998) and Michelson et. al. (1999) used similar models, the same data set and climate variables (average monthly precipitation and temperature) from seven western cities (Los Angeles and San Diego, CA; Broomfield and Denver, CO; Santa Fe, Albuquerque, and Las Cruces, NM). They found that temperature was a statistically significant determinant of water demand, but precipitation was not. In both papers the authors did not use separate regression equations for the water demands in each city. Nieswiadomy (1992), using data from 430 of the 600 largest U.S. utilities grouped into four regions, created three different water demand models based on different prices. He found that average monthly temperature was always significant in the West, but average monthly rainfall was only significant in the West using the marginal price model. Cochran and Cotton (1985), in a study of monthly water demand in Oklahoma City and Tulsa, OK, found that

3.02 Household and House Characteristics

As noted earlier, most demand studies focus primarily on the influence of price, and consider other factors such as weather only as necessary to control for their collective distortion of the price/demand relationship. Of these other factors, weather receives the greatest attention, especially in areas where outdoor landscape watering is a major component of overall use. Knowledge about how a given community of users responds to price and weather can be sufficient to then measure, at least generally, the influence of non-price policies such as restrictions and/or public education efforts (e.g., Renwick and Archibald, 1998). This is a logical and valuable research trajectory largely summarized in the preceding sections.

The sophistication, transferability, and utility of these investigations often hinges on the ability of researchers to model the remaining "demographic" factors that are well-known to influence demand (e.g., see summaries by Arbués et al., 2003; Cavanagh et al., 2002; and Lyman, 1992). This, in turn, often hinges on the availability of data. While aggregate (citywide) data can be useful in these investigations, customer level data provides significantly greater research opportunities[26]; as a practical matter, aggregate water demand is a function of the decisions of many individual water users, not all of whom are likely to respond to price, weather, and non-price policies equally. Not only do the characteristics of these water users vary from community to community, but they evolve within communities over longer time periods (a decade or more). This is an important consideration if demand studies are to influence future water planning in sophisticated ways and across multiple locales.[27]

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temperature and precipitation did not affect demand. (Only temperature in Tulsa was significant.) However, the authors felt that the weather variables might have been significant if they separated out customer classes, e.g. residential and commercial water users. Maidment and Parzen (1984), in a study of six Texas cities, similarly felt that the weather variables, especially evaporation and temperature, would have been more significant if they separated out residential water users or if they just looked at water use in summer months. Finally, Miaou (1990) looked at monthly water use in Austin, TX, and found that precipitation amount was significant in winter, but temperature and number of rainy days were not. He also found that the number of rainy days in a month was a better explanatory variable describing summer water use than rainfall amount.

[26] Schefter and David (1985), among others, have commented on the shortcomings of using aggregated data.

[27] As Cavanagh et al. (2002: 33) observe, "Several of the explanatory variables that have the greatest influence over daily demand are not variables that can be affected by utility water conservation policies or programs: here we refer especially to the size of a home, number of bathrooms, and number of residents in a household, and to a smaller extent, lot size and home age." In a related vein, Renwick and Green (2000: 51) conclude: "Further research on residential water demand is needed to address two important issues. First, more information is needed on how household characteristics influence policy responsiveness. Since water is a highly political good, the equity implications of alternative policy decisions are an important ingredient in the policy formulation process. Armed with this information, regional urban water policy planners can design a DSM program which achieves the required reduction in demand as efficiently as possible, given equity considerations. Second, since policy makers frequently adopt more than one policy during a water shortage, more research is needed to understand how the interaction of policy incentives influences the overall reduction in aggregate demand."

Many of these factors that deserve attention in demand studies can be described as *household* and *house characteristics*, with the former category including demographic characteristics of the water users themselves and the latter covering physical qualities of the structures served. For household characteristics, researchers can use data at either the family (household) or "head of household" scale, a decision based on available information and the nature of the water demand decision making process. As discussed below, key household characteristics include wealth (income), family size (and age distribution), and social attitudes. House characteristics of interest can include the age, type and size of the structures, and types of water using appliances employed.

(a) Household Characteristics

(i) Personal Wealth

The most widely studied of the demographic factors influencing water demand is personal wealth. Some measure of wealth (e.g., income) is often integrated into water demand studies, based on the assumption that greater wealth is likely to lead to an accumulation of water-using devices and, simultaneously, temper the influence of price in restricting water demand. Here it is worth reviewing the significance of personal wealth (income) independently as a key demographic factor in shaping demand, and consider the ways that this issue has been addressed in the literature.

As Piper (2003: I-2) observes, "almost all of the demand models have estimated the price elasticity of demand to be negative and inelastic and the income elasticity to be positive and inelastic. This general result has occurred regardless of the region where the study was conducted or the modeling technique used." Cavanagh et al. (2002) report that most income elasticities in the literature (1951 to 1991) generally fall in the range of 0.2 to 0.6.[28] Representative studies include those by Jones and Morris (1984) (0.40 to 0.55 in Denver, depending on the price model), Cochran and Cotton (1985) (0.58 for Oklahoma City), Billings and Day (1989) (0.33 in southern Arizona), Nieswiadomy (1992) (from 0.28 to 0.44 in the North Central, Northeast and South regions using the marginal price model), Renwick and Archibald (1998) (0.36, based on data from 119 single family households in two California cities over a 6-year period), and Renwick and Green (2000) (0.25 in 8 urban water agency service areas in California).[29] Howe and Linaweaver (1967) showed a similar range over 39 areas spread across the U.S., as well as demonstrating higher income elasticity for outdoor water use than indoor use.[30]

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[28] Note that an income elasticity of +0.2 means that a 10% increase in income increases water demand by 2.0% (all else remaining constant).

[29] Arbués et al. (2003: 87) document an even greater range in income elasticities. Data from 9 studies show values ranging from 0.05 to 7.83.

[30] Some of the other salient studies include Berry and Bonem (1974) (which used aggregate municipal water demand in over a dozen New Mexico towns), Lyman (1992) (using data from 30 households in Moscow, Idaho in pooled, time series, and cross section observations), and Foster and Beattie (1979) (using AWWA data from 218 cities nationwide). Berry and Bonem (1974: 1240) was among the first studies to explore the link between income and water demand, concluding: "[A]s income rises, more water-using appliances, such as dishwashers and garbage disposal units, may be installed; also there is more

One of the most intriguing studies is by Agthe and Billings (1997), who used surveys from Tucson water customers from 1979 and 1989 to aggregate household data into three income groups—low, middle and high—concluding that water demand in high income households exceed low income groups by 56% and middle income users by 37%. In this and many related analyses, the income/demand relationship is investigated with respect to other considerations, particularly factors such as increasing block rate structures which nest discussions of demand and income within the larger subject of price elasticities (e.g., Billings and Agthe, 1980).[31] (Price elasticities are discussed in Section 2.01)

In addition to income (usually per capita income derived from aggregated data), researchers often use other types of data to measure personal wealth, in part because some measures of wealth are thought to be more relevant to water demand than income, and in part because some statistics are more readily available at the household level than is personal income. Perhaps the most common of the surrogate statistics is the assessed value of the home (e.g., *see* Howe and Linaweaver, 1967; Lyman, 1992; Hewitt and Hanemann, 1995; Dandy et al., 1997; and Arbués et al., 2000). Other variables considered (often in conjunction with income or property value) are: lot size or some related measure of irrigated acreage (Hewitt and Hanemann, 1995), number of bathrooms (Cavanagh et al., 2002), square footage of the house (Cavanagh et al., 2002), or multi-faceted wealth indices (e.g., *see* Jones and Morris, 1984).[32] Home ownership is also a potentially significant measure of wealth.[33]

In all of this literature, the problem of multicollinearity is a real concern, as personal income/wealth is likely to be correlated with a variety of housing characteristics (e.g., number of bathrooms, lot size) (e.g., *see* Foster and Beattie, 1979; Martinez-Espineira, 2002).[34] Cavanagh et al. (2002) suggest that when the potential link between income and other housing characteristics is not considered, the typical result is the over-estimation of the influence of income on water demand.

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discretionary income available to be devoted to lawns, shrubs, and trees and to the purchase of lots with more room for landscaping. Finally, high-income areas may give rise to more commercial activity as total consumer expenditures increases."

[31] Agthe and Billings (1997) found that the instrumental price elasticities were different among each income group, and were significantly higher in the high (-0.54) and low (-0.55) income groups compared to the middle income group (-0.39). Presumably, the sensitivity of the high income group is due to their higher water use which exposes them to the highest pricing tiers and, perhaps, to their higher level of discretionary water uses. Members of the low income group, conversely, were unlikely to encounter the high pricing tiers, but were more sensitive generally to the cost of water in the family budget.

[32] The Jones and Morris (1984) index includes education and occupational level (of head of household), car ownership, assessed property value, and age of property.

[33] Billings and Day (1989) found as the percentage of residences occupied by a homeowner increased 10%, water use declined 1.8%, possibly because homeowners are more water conscious because, unlike renters, they pay water bills and can install water conserving fixtures. This explanation is likely more credible in situations where the renter does not pay the water bill; in the converse situation, the expectation is that renters may be reluctant to spend their own money maintaining the landscaping of a landlord.

[34] Note that Lyman 1992 found both household income and property value to be significant variables, and argued for using both on the ground that they measure related, but still different, things.

(ii) Family Size and Age Distribution

Two related considerations regarding family demographics and water demand are the size of the family (number of members) and their age distribution. This is not a highly active area of research (with much of the relevant literature from Europe), and is rarely the central focus in studies where it is addressed. Nonetheless, several studies confirm the intuitive hypothesis that household water demand increases as the number of members increases (Howe and Linaweaver, 1967; Foster and Beattie, 1979; Lyman, 1992; Nieswiadomy, 1992; Renwick and Archibald, 1998; Nauges and Thomas, 2000; Cavanagh et al., 2002; and Piper, 2003).[35] For example, Cavanagh et al. (2002) used data from 1,082 single-family homes in the U.S. and Canada to show that each additional household resident increases daily demand by 22%. The increase is not one-to-one due to economies of scale—i.e., doubling household members does not double water demand, as some major water uses (notably outdoor irrigation) is not family size dependent (Hoglund, 1999).

The significance of age distribution on water demand has primarily been studied in two investigations: Hanke and de Mare's (1982) study of Sweden, and Lyman's (1992) study of Moscow, Idaho. Hanke and de Mare found that the elasticity of water demand for adults (0.13) was more than twice that for children (0.05). Unlike Hanke and de Mare's study that only distinguished between adults and children, Lyman considered adults, children and teenagers (actually ages 10 to 20). While both studies show that adults use less water (per capita) than those under age 20, Lyman suggests that the highest users are actually children (those under age 10) and the lowest water users are teens (age 10 to 20). Lumping children and teens together, therefore, can hide an interesting water use dynamic. Lyman finds that adding a child to a home increases water usage by 2.5 times that of another teen and 1.4 times that of an adult.

Another interesting dynamic may occur as people enter retirement age. Billings and Day (1989) found levels of water use increased as individuals in the Tucson, AZ area transitioned from the 55-64 age range to the "post-retirement" class, possibly as an emphasis on work gives way to time at home and activities such as gardening. A seemingly contradictory result is found in Martinez-Espineira's (2002) study of cities in northwest Spain, where per capita use is lower in cities with a high concentration of people over age 64.

The need for additional research on this subject is evident, but is largely prohibited by the challenge of matching age distribution data to household consumption records. Some researchers have tried to use number of bathrooms as a surrogate statistic for household size; for example, Hewitt and Hanemann's (1995) study of summer water use in Texas found number of bathrooms was significant. This, however, raises a variety

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[35] Nieswiadomy (1992) found the number of persons per household was significant only in the South using the marginal price model, in the Northeast and West using the average price model, and only in the West using Shin's price perception model.

of methodological questions, including the possibility that number of bathrooms is correlated with other factors, namely income.

(iii) Attitudes about Water Use/Conservation

Decisions about water use are, in part, a function of attitudes about the social desirability of using (or conserving) water. Presumably, this factor is likely to be most significant in regions where water availability is a constant concern. One of those areas is Colorado's Front Range, where public opinion surveys consistently report a strong water conservation ethic. For example, in the City of Aurora's Resident Opinion Research (Corona Research 2004), 84.1% of respondents named social responsibility as one of the top three primary motivating factors causing them to conserve water. The next highest factor was to lower their water bill (72%), followed by concern the city will run out of water (47.2%). In a survey of Denver Water customers, 33% said they conserved because it was the socially responsible thing to do.[36]

These results should be viewed with caution, however, as they can be highly site-specific, and many studies suggest idealist motives often do not lead to actual conservation. For example, de Oliver (1999) found that the overwhelming expression of popular support for conservation (86%) in San Antonio, Texas was not reflected in action where the community's response to a demand management plan resulted in a 0.9% increase in water use. The author concludes at p. 387, "conservation as a policy has achieved the status of a valued aesthetic, so much so that expressing notions to the contrary is socially undesirable. But either due to inability or equivocation, this aesthetic did not effectively translate into manifested response to a conservation program." Similarly, Hamilton (1983) found more affluent, better-educated and younger households were more likely to express idealist motives, and that these motives were correlated with self-reported water savings behavior. (Hamilton's later study (1985) found that only 42% of respondents in Concord accurately reported whether their water use had increased, decreased, or stayed the same when compared to actual water consumption data.) However, these motives did not lead to actual water savings. In reality, higher income households tended to save less water than lower income households, though neither demographic variables nor conservation motives were as important in explaining actual savings as pre-shortage use. Households using more water to begin with saved more in absolute terms. While low-use households had less opportunity to make substantial reductions, their savings in percentage terms were higher. Syme et al. (2000) note the substantial literature indicating a weak correlation between having a motivation to conserve and actually conserving. However, researchers in one study reported by Syme found a drop in household water consumption when consumers learned that their favorable attitudes toward conservation did not match their actual water use, indidcating that conservation-minded consumers believe they are already conserving more than they are.

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[36] The survey allowed for multiple answers; social responsibility was only one of several factors reported.

In some situations, a desire to conserve water may be negated by classic common pool resource disincentives; for example, Corral-Verdugo et al.'s (2002) survey of 280 Mexican citizens found that the more people perceived that their neighbors wasted water, the less they conserved.

The relationship between water demand and social attitudes can also be a gateway to research on factors thought to influence the origins of an individual's values and ethics regarding water use. For example, it is a legitimate but largely unexplored research question about whether factors such as education, ethnicity and culture fundamentally influence values about water use, and more directly, do these qualities result in significant changes in actual water demand decisions.[37] To the extent that these questions are raised in the literature, they are rarely the central research focus, and are often considered in the context of demand management programs (discussed earlier in Section II.b).

(b) House Characteristics

Many features associated with type, age, size and features of homes are believed to influence household-level water demand. In many situations, however, it is difficult to obtain research datasets that allow for these influences to be examined in sophisticated ways, and in other situations, the strong correlation with these house characteristics and other influences, namely household wealth, make establishing statistically significant relationships difficult. Nonetheless, a variety of issues and studies are worth considering.

(i) Type of Dwelling

One factor that might influence household level water demand is the type of dwelling used by the family. Given the focus of this literature review on single-family homes, much of the potential variability on this topic is beyond our scope; even so, the literature is relatively thin on this subject, and generally considers this issue as part of studies more directly focused on price and income effects and water demand planning. One particularly salient question is the extent to which the ratio of single-family to multi-family homes affects per capita demand, an issue that arises in two contexts: first, when a researcher only has access to aggregate (citywide) data, and thus needs to make assumptions about average living conditions; and second, when the goal of research is to assess water demand trends in communities undergoing a transformation in housing stock.

Cochran and Cotton (1985), for example, tried to determine the impact of a trend away from single family housing toward multi-family dwellings in Oklahoma City and Tulsa, Oklahoma. They looked at the number of households per thousand population, and found it was a significant predictor of water demand as a single explanatory variable for

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[37] A few relevant studies include Griffin and Chang (1990) and Michelsen et al. (1999).

Tulsa, but lost its statistical utility when considered along with other variables (water price, per capita income). Woodard and Horn (1988) explored a similar topic in Phoenix and Tucson with interesting results. The growing percentage of multi-family dwellings in the overall housing portfolio of both cities was reducing per capita demand as expected in Phoenix but not in Tucson, presumably because lush landscaping and pools are common features of all Phoenix housing stock but are more typically only seen in Tucson in apartment buildings.

A similar consideration is whether the nature of water demand is a function of the urban versus suburban nature of the community. Martin and Wilder (1992) found urban users are more price elastic than suburban users (although both are generally inelastic). Similarly, Schneider and Whitlatch (1991) found that price elasticities were much higher in commercial, government and school uses than in residential or industrial uses. As Renwick and Green (2000: 51) noted, this issue can be of concern in the context of demand management planning: "Landscape use restrictions are expected to reduce demand more in suburban communities, where households maintain larger amounts of landscaping, than in higher density urban areas."

(ii) Age of House

As communities grow and age, they develop a housing stock of multiple ages. This influences water demand, perhaps accounting for "5 to 10 percent of the variation in residential water demand" (Cavanagh et al., 2002: 21). Generally, the observed relationship is that older homes use more water than newer homes.[38] For example, Billings and Day (1989) found a growing percentage of new homes in Tucson correlated with reduced water use, perhaps as a result of low water use landscaping and small yards. Similarly, Lyman's (1992) study of Moscow, Idaho found age of home was positively related to water usage, suggesting newer homes embody more efficient water-using goods.

The idea that older homes use more water than newer homes may be too simplistic. Mayer et al. (1999) and Cavanagh et al. (2002), for example, suggest a more complex relationship when homes are grouped into three categories: old, new, and "middle-aged." Using this approach, middle-aged homes (roughly those from the 1960s and 70s) emerge as the highest water users. Cavanagh et al. (2002: 21-22) explain:

> [V]ery old homes are likely to have smaller connections to their city water system, and also fewer water-using fixtures such as dishwashers and jacuzzis than do newer homes. The very newest homes are those built after the passage of local ordinances in the 1980s and 1990s requiring low-flow toilets and other water-conserving fixtures to be installed. Middle-aged homes should be the largest water users, as they were built with a taste for

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[38] Note that Nieswiadomy (1992) did not find a significant relationship, however, his analysis was based on a national 1984 database that did not feature much of housing stock influenced by water-saving building standards largely implemented in the 1980s and 1990s.

> high water use in mind and before water-conserving fixtures were required by law. We therefore expect the relationship between demand and home age to be non-monotonic.

Mayer et al. (1999) used this observation to suggest that homes built in the 1970s and 1980s were perhaps the best targets for retrofit and ultra low flow toilet rebates—older homes had probably already been updated, and newer homes already had efficient technology.

(iii) Size of the House and the Lot

It is frequently hypothesized that house size and lot size are positively correlated with indoor and outdoor water demand, respectively. Much of the available research, however, struggles to establish statistical significance among these intuitive relationships. Cavanagh et al. (2002), for example, found that every 1,000 square feet of house size in 11 urban areas in the U.S. and Canada[39] increased water demand by 13-15%, yet others, such as Hewitt and Hanemann (1995), found no significant relationship between house size and water demand in Denton, TX. A slightly different metric of house size—number of bathrooms—also offers inconsistent results. Cavanagh et al. (2002) found each bathroom increases demand by 6%; Hewitt and Hanemann (1995) also found the number of bathrooms significant and positively correlated with water demand. Lyman (1992), however, using data from 30 households in Idaho, found total number of bathrooms was negatively related to water usage, and was likely correlated with other variables such as property value.

A somewhat clearer picture exists regarding lot size (or related measures of irrigable acreage). Studies by Lyman (1992), Renwick and Green (2000), and Cavanagh et al. (2002) all found water demand increased with lot size. Cavanagh et al. (2002) detected only a modest increase, concluding that each additional 1,000 square feet of lot area increased household demand by less than 1%, while Renwick and Green (2000) found that a 10% increase in lot size yields a 2.7% increase in demand. However, as seen with many other household and house variables, many researchers, including Howe and Linaweaver (1967), ultimately throw irrigable acreage out of their demand model, believing it to be too closely correlated with housing value.

(iv) Home Technology

The technologies featured in water-using activities and devices are constantly changing, leading to differences in water demand. Given this observation, it should be possible to correlate household level demand with types and prevalence of different

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[39] These are Denver, CO; Eugene, OR; Seattle, WA; San Diego and Lompoc, CA; the areas surrounding Walnut and Calabasas, CA, Tampa, FL; Phoenix and Tempe/Scottsdale, AZ; and Waterloo and Cambridge, Ontario, Canada.

technologies found in the housing stock. However as seen before, this is not always easy to accomplish in a research setting, as data about technology distribution are often not available to researchers (and not reported along with household level consumption data), and the presence/absence of given technologies is often correlated with other household and house characteristics. Nonetheless, a variety of water demand models consider technology in some way, particularly with respect to outdoor water uses where higher price elasticities are consistently observed (e.g., *see* Howe and Linaweaver, 1967; Morgan and Smolen, 1976; Danielson, 1979; Foster and Beattie, 1979; Griffin and Chang, 1990; Lyman, 1992; Renwick and Green, 2000; and Arbués et al., 2003). In this sector, data about types of irrigation systems are particularly desirable (Lyman, 1992; Renwick and Archibald, 1998), as is data on the presence/absence of evaporative coolers (Cavanagh et al., 2002).

Many researchers have shown that adding lawn irrigation technology generally increases water demand (e.g., *see* Lyman, 1992; Mayer et al., 1999; Renwick and Archibald, 1998; and Cavanagh et al., 2002). Lyman (1992) and Renwick and Archibald (1998), for example, both found increases in water use among households with sprinkler systems (compared to those without), with the latter study suggesting an average of 9% higher demand. A more detailed review of irrigation technology by Mayer et al. (1999) found homes with in-ground sprinklers use 35% more outdoor water than those without; those that use an automatic timer use 47% more outdoor water than those that do not; homes that water with a hand-held hose use 33% less outdoor water than those that do not; and households with drip irrigation systems use 16% more water outdoors than those without such systems. Cavanagh et al. (2002) concludes that automated (programmable) systems increase use since these systems typically water at periodic intervals regardless of whether or not rain has recently occurred or is forecast.[40] As new technologies such as rain sensors, and ET and soil moisture meters begin to appear in the marketplace, new research is needed to correlate irrigation technology with demand.

Cavanagh et al. (2002) also comment on the significance of evaporative coolers, which in some circumstances can use as much 500 gallons/day. Without controlling for other variables, households with evaporative coolers use on average 40% more water than households without them, effectively substituting water for electricity to satisfy cooling demands. The authors note that evaporative coolers are quite common in many arid cities, and are most common among low income households. Specifically, they found evaporative coolers in 43% of sample households in Phoenix, one-third in Tempe and Scottsdale, and 14% in Denver. Mean annual income among households with evaporative coolers in this study was $56,000 compared to $71,000 in households without them.[41]

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[40] There are many reasons to believe that few homeowners apply water in appropriate levels. For example, Kiefer and Dziegielewski's (1991) review of 515 single-family households in Southern California found that only 11 percent watered landscaping within 10 percent of actual moisture requirements—39 percent over-irrigated by more than 10 percent and 50 percent under-irrigated by more than 10 percent.

[41] Higher income homes typically employ air conditioners.

The indoor technologies of interest are toilets, washing machines, and related low-flow plumbing fixtures. Most plumbing fixtures are covered by standards enacted in the Energy Policy Act of 1992 which, among other things, established a national standard for toilets of 1.6 gallons per flush.[42] Initial mandatory implementation of these standards began in 1994. Many states and municipalities have also enacted related standards, and voluntary rebate programs exist for a variety of indoor water-using technologies, including washing machines.

As Cavanagh et al. (2002: 6) note, water savings associated from these technological changes are frequently estimated from engineering studies using a sample of households. They report that "most of these studies used intrusive data collection mechanisms, attaching data collection equipment to faucets and other fixtures in homes. Study participants were aware that they were being monitored as they used water within the household, which may have led to confounding behavioral changes." Mayer and et al.'s (1999) Residential End Uses of Water study avoided some of this problem by using non-intrusive data loggers installed on the water meter of each study residence. The data allowed researchers to determine where, when, and how much water is used by a variety of household devices. However, participants were still aware they were being monitored.

4. Summary and Conclusions

The literature on residential water demand has expanded significantly in recent years in terms of scope and sophistication, as many quantitative, regression-based studies have illuminated many relationships while simultaneously identifying several new research questions. A consistent point of emphasis in the literature is the need to understand how price influences demand (price elasticity), a question of great practical importance as pricing provides an obvious mechanism for water utilities to strategically manipulate customer behavior. The tremendous experimentation recently with new rate and pricing structures has provided many opportunities for this research, with dozens of studies confirming the intuitive notion that raising prices reduces demand, albeit only modestly (i.e., demand is largely price inelastic). Estimates of "price elasticity"—the economic measure of how demand for a good responses to price—vary widely; one summary of this literature suggests a fairly typical value to be -0.5 (meaning that a 10 percent increase in price nets a 5 percent decrease in consumption).

Nested within this general conclusion regarding price elasticity are a variety of subtle, but practically important, uncertainties and research questions. Chief among these is the notion that many individuals lack a clear understanding of their rate structure and water bill, raising difficult research issues about which price signals customers actually respond to. In the modern era, most customers face an increasing block rate structure which means that water gets progressively more expensive as their level of use moves them into and through pricing tiers designed to discourage excessive use. The rationale of this approach is based on the notion that consumers respond to marginal prices (i.e.,

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[42] Energy Policy and Conservation Act of 1992, Public Law 102-486, October 24, 1992. 102nd Congress.

the cost of the last unit purchased), however, there is reason to think that this viewpoint is too simplistic, as customers not only often lack an understanding of their rate structure, but rarely have anything resembling real-time information about their current level of consumption. As rate structures continue to grow in complexity, this issue takes on greater salience. Additionally, it is increasingly clear that price elasticity can vary significantly among seasons, uses, regions, and various social/economic conditions. A more sophisticated understanding of these influences is key to translating a general understanding of price elasticity into effective demand management policies. Similarly, the interaction of price and non-price demand management programs is of particular concern, as many utilities employ multi-faceted programs to manage consumer demand for water.

The range of non-price strategies for managing water demand can generally be grouped into three categories: water restrictions, public education, and technological improvements. Research into the first category, water restrictions, generally focuses on the comparison of voluntary versus mandatory programs, usually focused on outdoor water uses during drought emergencies. The literature is consistent in showing significant (often 30 percent or more) savings from mandatory restrictions; findings regarding voluntary restrictions are much more variable, but with savings estimates generally lagging far behind the mandatory programs. Part of the challenge in assessing the impact of restrictions programs is that they are usually combined with other efforts, particularly public information campaigns. Research into these educational efforts generally show them to be modestly beneficial, especially in the short-term, but beyond that general conclusion it remains a challenge to (a) separate the effect of education programs from other pricing and non-price programs, (b) to make meaningful distinctions between the nearly infinite variety of educational efforts, and (c) to assess the long-term value of public education in promoting a conservation ethic. Research seems to suggest that a certain “critical mass” of educational programs are necessary to generate significant benefits, but that utilities soon reach a point of declining returns as additional efforts are implemented thereafter. Less confusion generally surrounds efforts focusing on technological changes, such as household-level retrofitting of water-using devices such as toilets, showerheads, and washing machines. Among these approaches, the significant water-saving benefits of toilet retrofits are best documented. As noted later, technological upgrades regarding outdoor sprinkler systems do not appear to offer similar conservation benefits.

Influencing the spectrum of price and non-price tools that utilities can potentially utilize to manage demand are a host of independent factors known to influence residential water demand. Chief among these is weather. It is well documented that weather can impact short-term water demand decisions (particularly for landscape irrigation), and for this reason, weather variables are typically controlled for in studies focused on price and non-price tools. But beyond the intuitive conclusion that hot-dry weather generates higher demands than cool-wet conditions, the exact nature of the weather/water demand relationship has several areas of uncertainty. For example, researchers continue to search for the best combination of weather variables to explain consumption patterns, often finding precipitation to be the most useful predictive variable, but also finding value in measures of temperature, ET (evapotranspiration), and in some cases, indices designed to measure the unmet water needs of landscape plantings. Exactly how to consider these variables is a challenging question; for example, what is more important: total precipitation over a month, the number of precipitation events, or the time between events? Questions of this nature are difficult to answer for a variety of reasons, including issues of microclimate (i.e., weather conditions in one neighborhood may not match another), the role that water plays in residential cooling systems (i.e., the prevalence of evaporative coolers), and distinguishing the impact of weather from the broad spectrum of pricing and non-price management tools that are most frequently (and/or aggressively) employed during the hottest and driest seasons. Furthermore, research is often frequently constrained by the fact that household-level consumption data is typically only available at a monthly scale while weather variables change daily.

Data limitations are also a common impediment to assessing the impact of demographic characteristics on residential water demand, as researchers rarely have data sets that allow them to match household level consumption data with demographic data about the people and house associated with a residential water account. Nonetheless, research to date is sufficient to suggest that the relevant household-level considerations likely include wealth (income), family size and age distribution, and household attitudes about water use and conservation. As intuitively expected, the literature is clear and strong in showing a positive relationship between wealth and water use. Similarly, it is not surprising that some research shows that income status influences how a household responds to price changes, although the nature of this complex relationship requires further study. Also suggesting further study is the relationship between household water demand and the size and age distribution of families. As expected, large families use more water than smaller ones, but the limited research available suggests that the age of family members may also be salient and in surprising ways. Limited research on household attitudes about water use is insufficient to support many conclusions, except that many (often most) individuals in a community express a water conservation ethic when surveyed, but that these values are often not translated into water-conserving behaviors, or if they are, may be the product of other influences (e.g., price signals) than ethical considerations. Better explaining household-level behavior may be key to improving demand management programs, and may require considering additional household level data such as education levels, ethnicity and culture, and processes of water-use decision making.

Several physical features of the homes in which customers reside can also influence residential water demand, but considering these factors in research can be difficult given the aforementioned lack of the relevant household/account level data, and given that many features of a home (e.g., size) are likely to be correlated with household features, particularly wealth (income). Nonetheless, to the extent that house characteristics are included in water demand studies, parameters of interest are usually type of dwelling, age of house, size of house/lot, and the water-using technologies featured. Given the emphasis of this literature review on residential water demand, our focus has mainly been on single family homes. Nonetheless, research that distinguishes water demand trends between single-family versus multi-family dwellings, between urban and suburban settings, and between purely residential and mixed residential/commercial regions can provide useful information, especially since it may influence the types of management options (e.g., customer-specific water billing) available to the utility, and may help illuminate how a community (and its water demand) will evolve over time. Even in a community dominated by single family homes that is not undergoing a transformation regarding the types or mix of dwellings, the addition of new homes and the aging of the preexisting housing stock is important. Generally, new homes are shown to consume less water than older homes—at least indoors where modern plumbing fixtures, many of which required under the Energy Policy Act of 1992, have resulted in significant savings. On the other hand, to the extent that newer homes are more likely to have automatic in-ground sprinkler systems, these technologies generally increase water demand when compared to homes reliant on hose-based irrigation technologies. The relative size of lots and homes is an important consideration, especially if these averages are changing as a community builds out and matures. As expected, larger lot sizes tend to be correlated with higher water demands; however, establishing a similar correlation between house size and demand has proven elusive.

Overall, the literature is clear in showing that residential water demand is largely a function of water price, the impact of non-price demand management programs, weather (and climate), and demographic characteristics of households and the homes they occupy. To the extent that this research is being pursued with the ultimate aim of informing and empowering water managers to better predict and manipulate demand, future investigations will need to better illuminate the interplay among these factors. This suggests a need to better understand water-use decision-making processes at the household level, which in turn will require the assembly of datasets featuring multiple, customer-level observations across time to augment citywide (aggregated) data. This seems particularly important as water utilities adopt dynamic, customer-specific water budgets, with the competing aims of managing water demand (and water revenues), encouraging economic efficiency in water use, all within a framework that customers can understand and endorse as equitable. To achieve these goals, in both "normal" and drought years, is a formidable challenge, and is deserving of the same level of intellectual effort as has traditionally been devoted to understanding and managing water supplies.

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