# Interannual Variability of Water Demand and Summer Climate in Albuquerque, New Mexico

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## ABSTRACT

The effects of interannual climate variability on water demand in Albuquerque, New Mexico, are assessed. This city provides an ideal setting for examining the effects of climate on urban water demand, because at present the municipal water supply is derived entirely from groundwater, making supply insensitive to short-term climate variability. There is little correlation between interannual variability of climate and total water demand—a result that is consistent with several previous studies. However, summertime residential demand, which composes about one-quarter of total annual demand in Albuquerque, is significantly correlated with summer-season precipitation and average daily maximum temperature. Furthermore, regressions derived from year-to-year changes in these variables are shown to isolate the climatic modulation of residential water demand effectively. Over 60% of the variance of year-to-year changes in summer residential demand is accounted for by interannual temperature and precipitation changes when using a straightforward linear regression model, with precipitation being the primary correlate. Long-term trends in water demand follow population growth closely until 1994, after which time a major water conservation effort led to absolute decreases in demand in subsequent years. The effectiveness of the conservation efforts can be quantified by applying the regression model, thus removing the year-to-year variations associated with short-term climate fluctuations estimated from the preconservation period. The preconservation regression provides a good fit to interannual summer residential demand in subsequent years, demonstrating that the regression model has successfully isolated the climatic component of water demand. The quality of this fit during a period of sharply reduced demand suggests that the conservation program has effectively targeted the nonclimatically sensitive component of water demand and has sharpened the climatically sensitive component of demand to a level closer to the consumption that is "climatically needed."

## 1. Introduction

The city of Albuquerque, New Mexico (hereinafter CABQ), is currently completely dependent on groundwater for its municipal water supply. The aquifer beneath the city is rapidly being drawn down, however, and the city has initiated plans to shift to surface water for a large fraction of municipal supply. A decade ago, in response to concerns over unsustainable water consumption and aquifer depletion, CABQ began to take serious steps to reduce demand for water.

After months of publicity, the city implemented a formal, comprehensive water conservation program in March of 1995. Educational efforts, direct incentives for reducing consumption, and price increases have all been implemented over the past decade. The overall program has resulted in clear decreases in water consumption since its inception. The city government is eager to strengthen conservation efforts to build on the current program. Several consecutive years of drought in the early twenty-first century have heightened civic awareness of water conservation, as debate over the reliability of future surface water supplies has intensified.

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Assessment of CABQ's water conservation efforts is complicated by the natural variability of water demand associated with weather and climate fluctuations. The extent to which interannual climate fluctuations influence water demand in CABQ, or elsewhere, is not well constrained. This study uses local climate and water demand data to develop a very simple regression model for estimating the effects of interannual climate variability on water use. The city's complete reliance on groundwater means that the *supply* of water is effectively decoupled from short-term climate variability, making it an ideal setting in which to examine the climatic effects on water *demand*.

Quantifying the interannual variability of water demand attributable to climate fluctuations can affect water management efforts in several ways. Such quantification would yield an estimate of the increase in consumption that might be expected in drought years of exceptionally high demand. Defining the climatic effect on demand could lead to inclusion of short-term climate forecasts in demand models as climate prediction skill improves. In the case of CABQ, specification of the climate-driven component of interannual demand variability can be used to improve assessments of the effectiveness of the city's recent water conservation programs.

Because of the influence of numerous economic, social, demographic, climate, policy, and psychological factors, comprehensive models for estimating and forecasting municipal water demand can be very complex. Much effort has been focused on economic and other policy variables (especially price of water), in large part because such variables can be controlled and manipulated by water utilities (Howe and Linaweaver 1967; Espey et al. 1997; Cavanagh et al. 2001).

The possible influence of climate variability on water demand is comparatively poorly understood, and may be very different in various climatic regimes. Many studies include climate data merely to account for average seasonal changes in use. Different climate variables have been used as demand predictors. 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. The city of Albuquerque presents an excellent setting for isolating the effects of climate on water demand, because its groundwater supply is buffered from short-term climate variability.

Some studies find that climate plays a trivial role in water demand. A general regression analysis of municipal water demand in New Mexico towns, including Albuquerque, found neither price of water nor a climatological variable (moisture deficit: potential evapotranspiration minus effective rainfall) to be a significant predictor as compared with per capita income (Berry and Bonem 1974). Cochran and Cotton (1985) also found a climate variable to be insignificant in a study of two Oklahoma cities but determined some elasticity to price. Neither of these studies disaggregated municipal water demand into customer classes; the importance of this approach will be discussed in section 2. Michelsen et al. (1999) and Gegax et al. (1998) found precipitation to be insignificant and average temperature to be slightly significant in their econometric study of the effectiveness of conservation programs in seven western cities, including three in New Mexico. Michelsen et al. (1999) considered the characteristics of summer rainfall events in this region (nonuniform, brief, and infrequent, with evapotranspiration rates much greater than precipitation) to be such as to alter residential watering patterns insignificantly.

Other regional studies have found climate to be an important factor in water demand, however. Anderson et al. (1980) examined water demand in Fort Collins, Colorado, to determine the effectiveness of water restrictions during a drought. They found that high rainfall and cooler temperatures reduced water use, estimated that more than one-half of the decrease in demand during the period of water restrictions might be attributable to climate variability, and concluded that the principal effect of the restrictions may be just to shift the timing of water use.

Woodard and Horn (1988) studied the effects of climate and weather on municipal water demand in Arizona. They found that several climate variables are important determinants of municipal water demand. Their modeling used measures of evapotranspiration, effective rainfall, cooling degree-days (CDD), and other variations of temperature and precipitation. Pan evaporation was key to determining irrigation demand while demand for evaporative coolers and cooling towers was related to CDD. An important fact for this study is that Woodard and Horn (1988) found that summer monsoon precipitation and, for daily usage, just the forecast of precipitation significantly determine water demand. Their study suggested that future improvements in quantitative daily precipitation forecasts should enhance residential water conservation efforts.

The most important climate determinant in the Woodard and Horn (1988) study was the number of precipitation events rather than the total amount of precipitation. Billings and Day (1989) also found that both temperature and precipitation are correlated with residential water use in Tucson, Arizona, and that the temperature correlation was principally significant above a minimum threshold temperature.

Maidment and Parzen (1984) found that monthly water use in several Texas cities (in the semiarid high-plains region of the state) was correlated with rainfall and pan evaporation. Wilson (1989) found that a 1% increase in moisture deficit corresponded to a 1.3% increase in water demand in Fort Worth, Texas. Rhoades and Walski (1991) used regression analysis to project pumping in Austin, Texas, using CDD and total rainfall, logarithmically transformed, as predictors. They note that determining the influence of climate on water demand is complex because outdoor water use depends on the duration and intensity of rainfall and the characteristics of temperature. In addition, soil moisture conditions depend on the interval between rainfall events. Billings and Agthe (1998) also developed a regression model for demand in Austin based on monthly departures from climatological rainfall and temperature values.

From these studies, a general consensus emerges that high precipitation should decrease water demand and high temperature should increase water demand. The usefulness of these variables is often improved by better defining their occurrence and magnitude, incorporating lag effects and thresholds, and using nonlinear and time series methods.

This study examines climate and water demand in CABQ at the seasonal time scale, focusing on summertime residential demand. The basic climate and demand data are described in section 2, emphasizing the need to consider just a climatically sensitive subset of total annual municipal water use. The assessment of climate–demand relationships that follows in section 3 relies on a simple but effective temporal filter to reduce long-term trends in demand (which are dominated by population growth) and to emphasize higher-frequency climatic fluctuations. The regression model is derived from the period of time prior to the city's major water conservation initiative; the application of this model to postconservation demand data leads in section 4 to some interpretive comments on the effectiveness of CABQ's conservation efforts.

## 2. Water demand in Albuquerque

The city of Albuquerque is located in north-central New Mexico, in the valley of the southward-flowing Rio Grande (Fig. 1). An extensive aquifer system underneath the city is the sole source of the municipal water supply. However, over the past decade new hydrological research and monitoring have shown that the extent of productive aquifer is much less than was previously thought (Bartolino and Cole 2002), and CABQ is moving aggressively toward extraction of surface water from the river to augment the city's water supply. Facilities to extract, purify, and convey river water are now under construction. For the period of this study, groundwater provides 100% of Albuquerque's water supply.

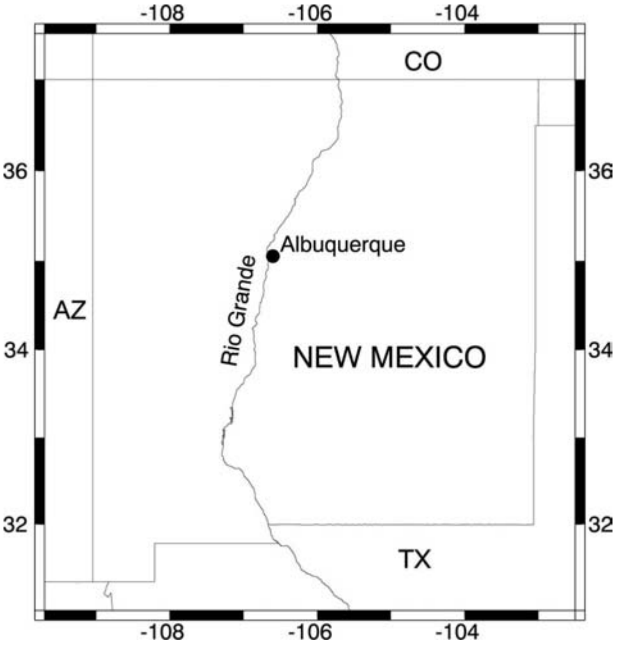

FIG. 1. Location of New Mexico, the city of Albuquerque, and the Rio Grande.

Total annual demand of CABQ water since 1930 exhibits a pronounced increase with time until the mid-1990s (Fig. 2a). "Water demand" is defined here in terms of metered residential customer accounts, based on monthly water bills issued by CABQ. There are several significant sources of uncertainty in quantifying total and per capita water demand. Billing periods are not exact months because the meter-read cycles overlap months. Some monthly bills are estimated. Most, but not all, residents and institutions within the city limits are customers of CABQ water. On the other hand, the CABQ water system extends beyond the city limits in some areas. In addition, census data for the city contain significant uncertainties and are not comprehensively updated each year; therefore, year-to-year population-change estimates are highly smoothed (Fig. 2). Thus, it is impossible to derive completely accurate per capita water demand estimates because existing population data do not correspond exactly to water demand data. These uncertainties could have substantial effects on the analysis to follow.

The upward trend in water demand throughout most of the twentieth century follows closely the increase of the city's population (Fig. 2a). It is readily apparent

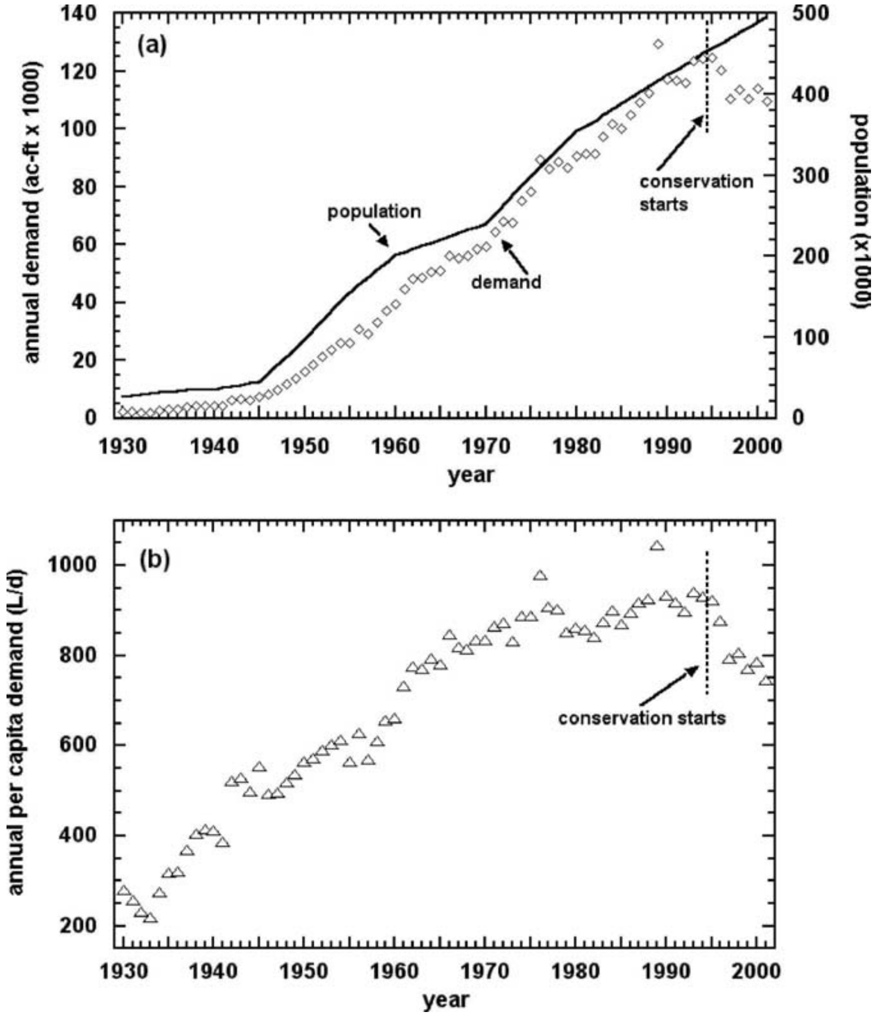

FIG. 2. (a) Total annual water demand $W_{\mathrm{ann}}$ (ac ft $\mathrm{yr}^{-1}$, diamonds) and population (solid line) for Albuquerque, NM, 1930–2001. (b) Annual per capita water demand (L $\mathrm{day}^{-1}$), derived from data in (a). Dotted vertical lines indicate the imposition of water conservation measures in Albuquerque after 1994.

from the time series in Fig. 2 that the conservation program that began in 1995 has been effective. Following three consecutive years in which total annual water demand exceeded 120 000 acre feet,[1] demand declined after 1995 to around 110 000 ac ft $\mathrm{yr}^{-1}$. This decrease occurred during a time of continued population growth, so that a plot of per capita demand (demand/population) makes the years since the conservation program was established stand out prominently (Fig. 2b).

It is obvious, and certainly not surprising, that population is the single largest factor determining long-term trends in total water demand. To isolate the component of demand that is related to climate variability, it is typically necessary to remove the effects of population growth, which is generally accomplished by considering per capita consumption statistics. Even on a per capita basis, however, we find that total annual consumption is only weakly correlated with local interannual climate variability, consistent with several of the previous studies on climate and water demand cited in the introduction. For example, during the most recent 22 yr (the period of record used for the results that follow), the Pearson correlation between annual per capita water consumption and annual temperature anomalies was

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[1] An acre foot (abbreviated here as ac ft) is the volume covering a surface area of 1 acre (4047 $\mathrm{m}^2$) to a depth of 1 foot (0.305 m). It is the native unit used in many water resource applications in the United States. One ac ft $\approx 1.233 \times 10^3\ \mathrm{m}^3 = 1.233 \times 10^6$ L of liquid water.

0.26; the corresponding correlation between annual consumption and precipitation anomalies was 0.01.

To identify a significant climatic influence on water demand it is necessary to consider just a subset of total annual demand. Monthly demand data separated by usage category were available from CABQ only since 1980. For the 1980–2001 period (22 yr), we found that summertime residential demand is by far the most sensitive component of the total to climate variability—a result that has been noted in previous studies. Residential demand accounts for slightly more than one-half of total demand in CABQ (Table 1). As suggested by the consumption subclass values in Table 1, economic activity in Albuquerque is focused more on service and professional sectors than on heavy industry, making the climatic sensitivity of water demand in CABQ potentially higher than in cities that are more heavily industrialized. Nonresidential demand (commercial, industrial, and institutional) exhibits a weak seasonal cycle and no particular relationship with year-to-year climate variability. In general, outdoor water use is heavily influenced by climate. Indoor use is relatively constant throughout the year.

Monthly average demand by residential customers peaks in early summer and reaches a winter minimum from December through February (Fig. 3a). Peak summer residential demand is nearly triple the winter minimum demand. Residential demand peaks during the summer because of outdoor water used for landscaping and evaporative cooling systems—uses that are very climate sensitive. About 49% of total annual residential demand occurs during the four summer months from June to September. Therefore, residential demand is roughly one-half of total demand in CABQ (Table 1), and one-half of total residential demand occurs in the peak summer months (Fig. 3a), so that about one-quarter of total demand is potentially sensitive to climate variability. This statement is meant to be merely an approximate estimate of the fraction of municipal demand that is climatically sensitive; some components of watering in parks, and perhaps some other nonresidential demand, may also be affected by climate variability. Summer [June–September (JJAS)] residential demand in CABQ will be the focus of the remainder of this paper.

TABLE 1. Components of municipal water demand in Albuquerque (1996–99 average). Average annual consumption during this period was 113 000 ac ft ($1.4 \times 10^{11}$ L).

| Usage category | Percentage of total demand |
|---|---|
| Residential | 53.8% |
| Commercial | 28.5% |
| Institutional | 9.8% |
| Industrial | 2.8% |
| Other (parks, municipal use) | 5.1% |

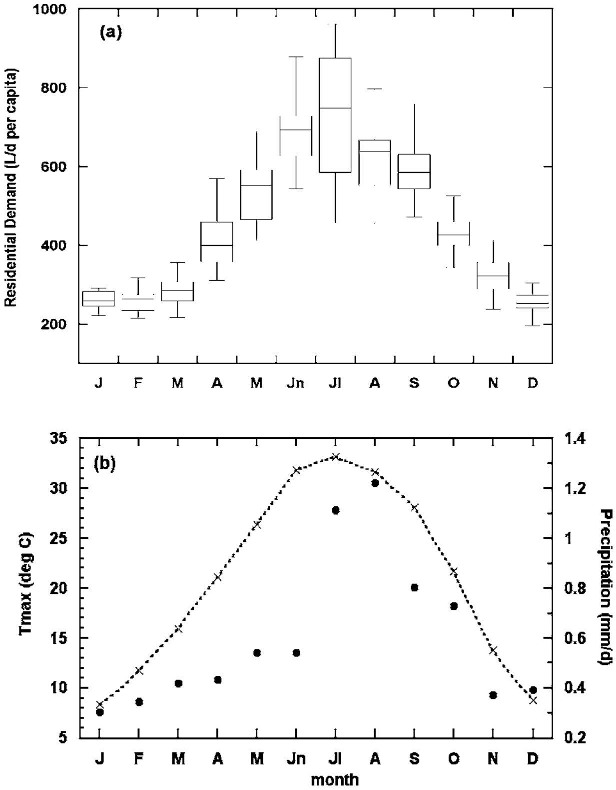

FIG. 3. (a) Distribution of billed monthly residential water demand (L $\mathrm{day}^{-1}$ per capita) for the period of 1980–2001 for each calendar month. The boxes demarcate the upper and lower quartiles of monthly residential demand, median monthly values are indicated by the horizontal line within each box, and the maximum and minimum values for each month are delineated by the whiskers. (b) Average daily maximum temperature $T_{\max}$ (°C; times signs connected by dotted line) and average daily precipitation rate $P$ (mm $\mathrm{day}^{-1}$; dots), for each calendar month, as observed at the National Weather Service office at the Albuquerque airport.

## 3. Interannual variability of summer residential demand and climate

Precipitation, temperature, and humidity variables were used to characterize local climate variability, based on measurements taken at the National Weather Service office at the Albuquerque International Airport at the southern edge of the city. These data were obtained from the Western Regional Climate Center and the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center. More than 40% of annual precipitation occurs during the summer months of July, August, and September (JAS) throughout central and southern New Mexico (Douglas et al. 1993). At the Albuquerque airport the monthly average precipitation rate jumps from about 0.5 mm day$^{-1}$ in June to more than 1 mm day$^{-1}$ in July and August and then decreases to around 0.8 mm day$^{-1}$ in September (Fig. 3b). Average daily maximum temperature ranges from less than 10°C in December and January to more than 30°C in June, July, and August (Fig. 3b).

Comparison of Figs. 3a and 3b shows that residential water demand generally follows the seasonal cycle of maximum temperature, increasing rapidly during the spring months and peaking in July. The abrupt increase of precipitation from June to July (Fig. 3b), associated with the onset of the summer monsoon, does not correspond to a decrease in demand (Fig. 3a). The apparent insensitivity of monthly demand to increased precipitation could indicate that climatological monsoon precipitation is insufficient to meet residential watering needs (Michelsen et al. 1998) but could also be due, at least in part, to demand data uncertainties associated with monthly billing cycles (J. Witherspoon, City of Albuquerque, 2004, personal communication). Demand decreases in late summer somewhat more rapidly than temperature in response to higher precipitation rates in August and September relative to May and June.

The covariability of interannual summertime climate and water demand fluctuations was analyzed using ordinary least squares linear regression analyses (Hirsch et al. 1993). Demand values were aggregated into monsoon-season variables for various combinations of summer months and were compared with aggregated meteorological variables for the same months. Many different combinations of variables and summer months were considered (Nims 2002). The summer season was defined over the four peak residential demand months (JJAS) or over three months [June–August (JJA) or JAS]. Seasonal water demand data were analyzed both in terms of total demand and on a per capita basis. Climate variables considered were derived from temperature data (daily average, average daily maximum, or seasonal cooling degree-days), precipitation data [average daily rate, natural logarithm of seasonal total, or number of days with more than 0.1 in. (2.54 mm) of precipitation], and humidity data (dewpoint or relative humidity).

TABLE 2. Linear regression models for summer-season (JJAS) residential water demand, derived from average maximum temperature $T$ (°C) and/or average daily precipitation rate $P$ (mm day$^{-1}$). All regressions are of the form $y = a_1x_1 + b$ or $y = a_1x_1 + a_2x_2 + b$ and are based on 15 yr of data (1980–94, before CABQ initiated its water conservation programs). As described in the text, predictand $y$ represents either seasonal demand anomaly $W'$ or year-to-year change $\Delta W$, subscript $t$ denotes actual demand (units ML day$^{-1}$), and subscript $c$ denotes per capita demand (liters per day per person). Corresponding predictors are seasonal temperature and precipitation anomalies $T'$ and $P'$ or year-to-year changes $\Delta T$ and $\Delta P$. Each regression was applied to independent data for the 7-yr postconservation period of 1995–2001. The fractions of interannual variance of $W'$ or $\Delta W$ accounted for by each regression model, calculated separately for the 1980–94 and 1995–2001 periods, are shown in the right-hand columns of $r^2$ values. All regression models listed satisfy an $F$ test for overall significance at the 5% level.

| Regression No. | Regression model | 1980–94 $r^2$ | 1995–2001 $r^2$ |
|---|---|---|---|
| 1a | $W'_c = 20.6T'$ | 0.25 | 0.33 |
| 1b | $W'_c = -79.4P'$ | 0.28 | 0.08 |
| 1c | $W'_c = 10.8T' - 61.7P'$ | 0.40 | 0.45 |
| 2a | $\Delta W_t = 15.2\Delta T + 3.9$ | 0.31 | 0.78 |
| 2b | $\Delta W_t = -35.4\Delta P + 3.6$ | 0.61 | 0.84 |
| 2c | $\Delta W_t = 5.5\Delta T - 30.6\Delta P + 3.7$ | 0.64 | 0.90 |
| 3a | $\Delta W_c = 37.4\Delta T - 2.7$ | 0.32 | 0.89 |
| 3b | $\Delta W_c = -85.1\Delta P - 3.5$ | 0.62 | 0.78 |
| 3c | $\Delta W_c = 14.6\Delta T - 72.6\Delta P - 3.1$ | 0.65 | 0.91 |

A sample of the principal results of these regression analyses is given in Table 2. Coefficients $a_1$ and $a_2$ have a positive sign if positive values increase water demand (e.g., temperature) and a negative sign if positive values of the predictor tend to reduce water demand (e.g., precipitation). Only results based on a 4-month summer season (JJAS) are shown. The results are not qualitatively sensitive to the definition of summer, although JJAS results were slightly better (higher $r^2$ value, as defined in Table 2) than those of JAS and were considerably better than the JJA results. Results were also similar for different temperature-related and precipitation-related variables. Considering the similar results, we have chosen to emphasize seasonal precipitation rate and average maximum temperature as regression predictors, because these variables are commonly measured and archived, offering long periods of record at many locations for future comparative studies.

Temperature and precipitation are not independent variables. Summertime temperature and precipitation fluctuations are inversely related (Pearson correlation = −0.47) in the Albuquerque record (Fig. 4a). Summers tend to be hot and dry, or cold and wet, throughout the Southwest. It could be possible to combine temperature and precipitation into a single variable for regression purposes—a possible avenue of future research.

Models 1a, 1b, and 1c in Table 2 describe JJAS residential per capita demand anomalies $W'_c$ (L day$^{-1}$), modeled in terms of seasonal anomalies of average daily maximum temperature $T'$ (°C) and daily precipitation rate $P'$ (mm day$^{-1}$). The one-predictor models

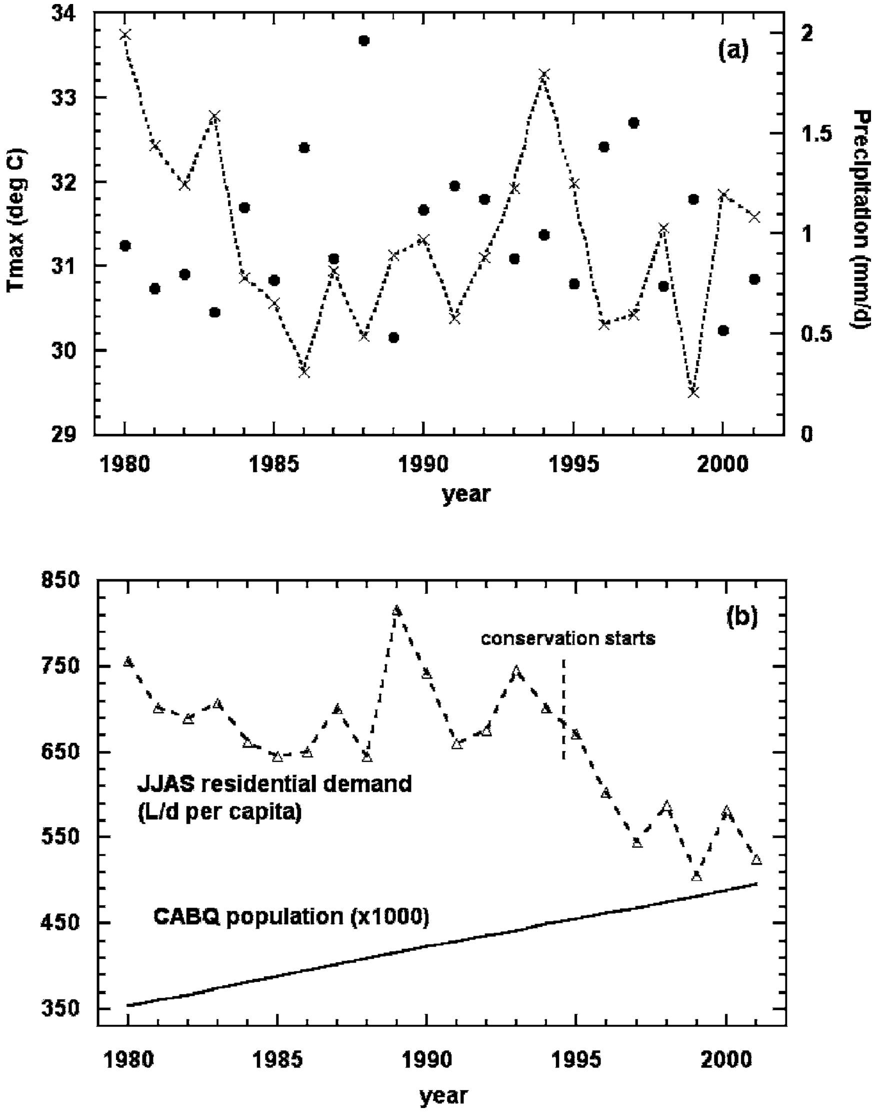

FIG. 4. (a) Summer-season (JJAS) average daily maximum temperature $T_{\max}$ (°C; times signs connected by dotted line) and average daily precipitation rate $P$ (mm day$^{-1}$; dots) for 1980–2001. The linear correlation between all values of $P$ and $T_{\max}$ is $-0.47$. (b) Summer-season (JJAS) per capita residential demand $W_c$ (L day$^{-1}$; triangles connected by dotted line) and Albuquerque population (solid line) for 1980–2001.

based on either $T'$ (1a) or $P'$ (1b) each account for about one-quarter of the variance of $W'_c$ in the 1980–94 period over which the regression models were derived. The near equality of $r^2$ values for models 1a and 1b suggests that maximum temperature and average precipitation are roughly equal in importance as predictors of demand anomalies. The two-predictor model accounts for more variance, as it must. However the $r^2$ value for the two-predictor model (0.40) is considerably less than 2 times the values of the one-predictor models, indicating that $T'$ and $P'$ are not statistically independent predictors, as discussed above.

Although demand and population are closely correlated on multidecadal time scales (Fig. 2a), this is not the case on shorter interannual time scales. As Fig. 4b illustrates, population tends to change slowly and steadily as compared with summer residential demand. Note that $W'_c$ exhibits a very large range of annual values between 1980 and 2001, from a minimum value of around 500 L day$^{-1}$ to a maximum of more than 800 L day$^{-1}$, due both to climate variability and to other factors such as conservation. Some of the smoothness in the population time series may be an artifact of its annual estimation; nevertheless, Fig. 4b clearly shows that the high-frequency (year to year) component of demand cannot be related to population changes.

We therefore hypothesized that the variability of demand related to climate should be most pronounced in the high-frequency component of the annual time series. Additional regression models were thereby derived using the *change* in water demand from the previous year ($\Delta W_c$) as the predictand and the *changes* in climate variables from the previous year ($\Delta P$ and $\Delta T$) as the predictors. Examining year-to-year changes of the variables acts as a crude but simple high-pass filter that can be implemented in real time.

The regressions for year-to-year demand changes, corresponding to models 1a, 1b, and 1c for demand anomalies, are listed as models 2a, 2b, and 2c (for actual demand anomalies) and 3a, 3b, and 3c (for per capita demand anomalies) in Table 2. The models that include $\Delta P$ as a predictor now account for considerably more demand variance than do the models of per capita demand based on $P'$ (more than 60% for 2b, 2c, 3b, and 3c as compared with just 40% for 1c). This result illustrates the sensitivity of seasonal residential demand to the large variability of precipitation in Albuquerque from year to year (Fig. 4a). Precipitation emerges as the primary predictor for interannual changes in demand. Models 2b and 3b, or 2c and 3c, yield very similar $r^2$ values, suggesting that population growth does not dominate the demand regression over the short period of dependent data. However, Fig. 2 clearly (and unsurprisingly) shows that population and demand are highly correlated in the longer record; therefore we will consider per capita statistics (model 3) as being probably more robust over the long term.

The subsequent discussion and illustrations will focus on regression 3c, which, of all the models in Table 2, accounts for the most variance in both the dependent and independent data periods. The regression equation is

$$\Delta W_c = 14.6\Delta T - 72.6\Delta P - 3.1,$$

where $\Delta W_c$ is the modeled change in per capita JJAS residential demand (L day$^{-1}$) from the previous year, $\Delta T$ is the change in seasonal maximum temperature (°C) from the previous year, and $\Delta P$ is the change in seasonal precipitation (mm day$^{-1}$) from the previous year. According to this model, when precipitation and maximum temperature are considered jointly, then each degree of seasonal temperature change is associated with 14.6 L day$^{-1}$ of demand change (higher temperature, more demand) and each millimeter per day of precipitation change is associated with −72.6 L day$^{-1}$ of demand change (more precipitation, less demand).

Comparison of $r^2$ values in models 3a and 3b in Table 2 indicates that precipitation is the primary predictor of $\Delta W_c$ in most years. Scatterplots of $\Delta W_c$ versus $\Delta P$ and $\Delta W_c$ versus $\Delta T$ clearly show the stronger linear relationship between the demand change and precipitation change (Fig. 5). These scatterplots also demonstrate that the relationships among these variables are not just the result of one or two outlier years. Furthermore, the scatterplots indicate that the covariability of water demand and climate variables in the postconservation

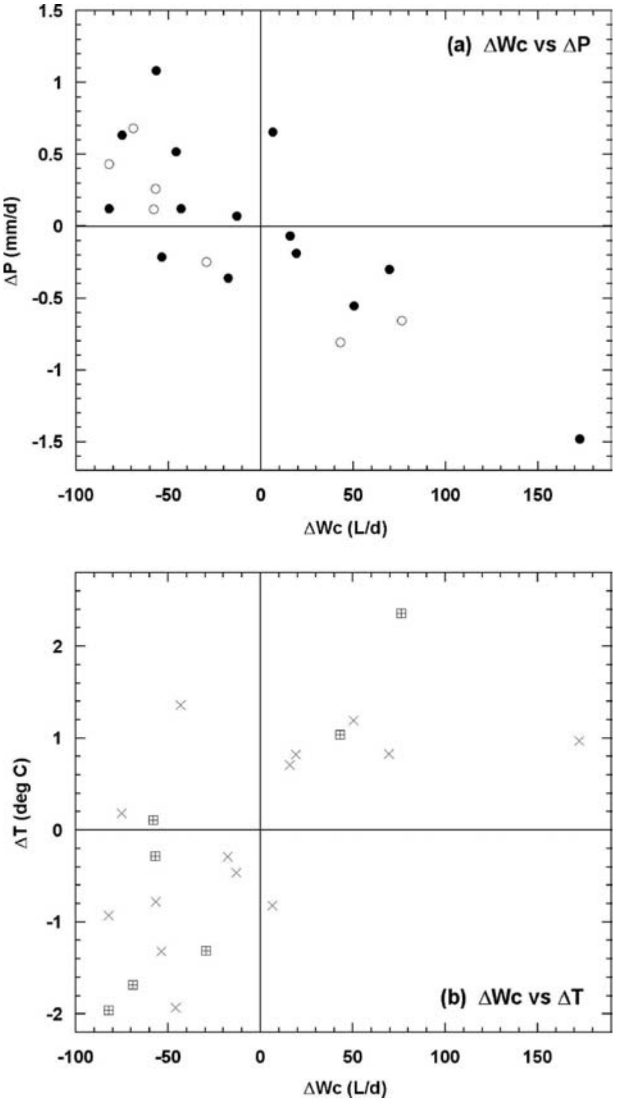

FIG. 5. (a) Year-to-year changes of JJAS per capita residential demand $\Delta W_c$ (L day$^{-1}$) plotted against year-to-year changes in JJAS average daily precipitation rate $\Delta P$ (mm day$^{-1}$). Solid dots are for 1981–94 period used to formulate model 3c in Table 2; open circles are for 1995–2001 period. The linear correlation between all values of $\Delta W_c$ and $\Delta P$ is −0.80. (b) As in (a), but for $\Delta W_c$ plotted against year-to-year changes in JJAS average daily maximum temperature $\Delta T$ (°C). Data for 1981–94 period are plotted with times signs; squares are plotted for 1995–2001 data. The linear correlation between all values of $\Delta W_c$ and $\Delta T$ is 0.67.

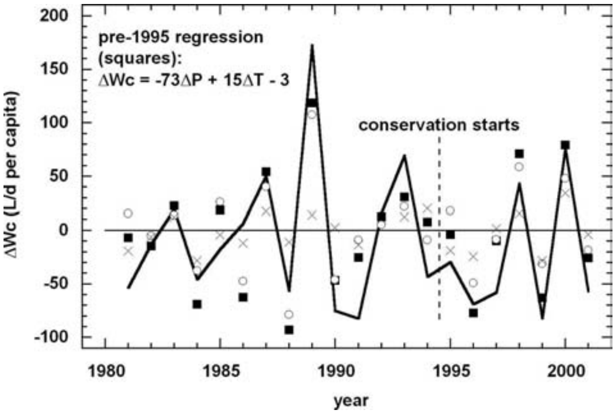

FIG. 6. Component terms of regression model 3c in Table 2, in units of the predictand $\Delta W_c$ (L $\text{day}^{-1}$): $15\Delta T$ (times signs) and $-73\Delta P$ (open circles), shown together with modeled $\Delta W_c$ (squares) and observed $\Delta W_c$ (solid line).

years (1995–2001) is not visibly different from that in the preconservation years (1981–94)—a point to be discussed further in the next section.

Time series of the terms in this model are shown in Fig. 6. A perfect model of demand change would have the modeled $\Delta W_c$ (the squares in Fig. 6) coincide exactly with the observed changes (shown as a solid line). Although the model is certainly not perfect, the modeled and observed $\Delta W_c$ values have the same sign in 12 of 14 preconservation years and in all 7 postconservation years. The primary importance of precipitation for this regression is indicated by the greater amplitude of the precipitation term (open circles) in comparison with the temperature term (times signs). In most years, the temperature and precipitation terms both favor demand change anomalies of the same sign, indicating the general out-of-phase relationship of $\Delta T$ and $\Delta P$. The year 1981 provides an example of the temperature and precipitation terms not following this relationship: summer residential demand decreased in 1981 relative to 1980 despite a decrease in precipitation but consistent with a pronounced drop in temperature following a very hot summer in 1980 (Fig. 4a).

## 4. Assessment of Albuquerque's water conservation program

The CABQ water conservation program has been effective, as is clearly seen in the time series for total annual demand (Fig. 2a) or summer residential demand (Fig. 4b). For the 5 yr prior to the conservation program (1990–94), total year-round per capita demand was 948 L $\text{day}^{-1}$ (Fig. 2b); after 2 yr of substantial decrease, per capita demand over the last 5 yr of data (1997–2001) was 781 L $\text{day}^{-1}$—a reduction of 21%. The 1990–94 and 1997–2001 JJAS per capita residential demand averages were 705 and 549 L $\text{day}^{-1}$, respectively, decreasing 28% (Fig. 4b).

Regression model 3c is derived from preconservation data (1980–94) but nevertheless provides an outstanding fit to postconservation data despite the overall reduction in demand. The fraction of interannual variance of $\Delta W_c$ explained by model 3c (the $r^2$ value in Table 2) actually *increases* in the independent dataset to more than 90%. Furthermore, the mean bias of the regression model applied to postconservation demand data is positive but remarkably small: the modeled summer residential demand for the postconservation period overestimates actual demand changes by just 21 L $\text{day}^{-1}$ per capita. The postconservation years do not stand out in the scatterplots in Fig. 5. Overall, then, the regression of year-to-year temperature and precipitation changes onto summer residential demand seems remarkably robust, albeit when applied to a small independent postconservation data record.

These results indicate that the estimated effects of year-to-year climate variability on summer residential demand are nearly unchanged as the result of conservation measures. We therefore deduce that the decreased demand in recent years, so evident in Figs. 2 and 4b, is coming almost entirely from the components of demand that are *not* captured by the climatic regression model. In other words, the interannual modulation of demand by short-term climate variability persists, and is even strengthened, by longer-term modulation of demand by conservation measures.

Considering the short 7-yr period of independent, postconservation demand data, it is certainly possible that the improvements in predicted demand provided by the climatic regression model occurred by chance. However, a much more interesting possibility can be postulated as the working hypothesis for future study. In addition to decreasing overall demand, it seems that another immediate effect of a successful conservation program may be to sharpen climatically sensitive residential demand rates closer to a "climatically needed" level. From this perspective, the 28% decrease in JJAS residential demand in the postconservation years represents "excess" water use. In other words, the improvement in the fit of climatically predicted demand changes to actual demand changes may actually be a consequence of an effective water conservation program.

City water managers would ultimately like to change water use patterns to decrease the consumption that is "climatically needed" (e.g., by replacement of high-water-use landscaping with xeriscaped vegetation). Such decreases in summer residential demand will take longer to implement than the more immediate reduction in excess use. The preconservation climatic predictors described in model 3c may then be expected to change (i.e., the absolute values of $a_1$ and $a_2$ would be expected to decrease) over a longer period of time than the 7 yr of postconservation data available to us.

## 5. Summary and conclusions

Water demand in Albuquerque was shown to have an obvious long-term trend related to population growth and a seasonal cycle with a maximum in early summer. Water use increases dramatically during the summer, principally because of increased outdoor water use. Regression techniques were used to evaluate the interannual covariability of climate and water demand, addressing large uncertainties in the existing literature regarding the importance of climate variability on water use. CABQ presents an excellent case study of water demand because its water supply (entirely groundwater) is currently decoupled from short-term climate variability.

The results of linear regression models of total water demand, based on many different climate variables, yielded weak and inconclusive results. However, the climatic modulation of interannual demand fluctuations became clear when just summer residential water demand was considered as the predictand. Both seasonal precipitation and average maximum temperature are correlated with summer residential demand. Analyzing the relationships between water demand and climate based on the change in the variables from the previous year is an effective high-pass filter that emphasizes the climatically sensitive fraction of water demand. Using per capita water demand also reduces the long-term trend related to population growth.

A more refined model of the effects of climate on water demand within Albuquerque would incorporate measurements from other sites within the city to characterize better the spatial variability of temperature and (especially) precipitation. The isolated, brief, and often random nature of summer precipitation in the form of thunderstorms distributes precipitation with tremendous variability. A cooperative observing station on the eastern edge of the city (in the foothills of the Sandia Mountains) receives 1.4 mm day$^{-1}$ of summer precipitation, on average, while a corresponding station along the Rio Grande receives only 60% of that amount. Other topographic gradients generate additional localized variability within the city. Microclimatic variability within CABQ may help to explain the variability of water use within the city, and linking the patterns of water demand and climate might lead to improved system operation at real-time intervals. As CABQ prepares to incorporate surface water into its municipal system, better insight into the influence of climate on water demand can lead to better system management.

The results of this study provide working hypotheses for demand models for other locales. Most current water demand models assume a stationary, average climate; this research may enable more detail to be put into these models or may even suggest more appropriate models. Moreover, these results can help water managers to evaluate conservation programs, pricing policies, fiscal obligations, and supply requirements and can provide a background for scenario studies of climate variability and climate change.

Demand models such as those developed in this study could be directly linked to prediction of climate anomalies. At present, the skill of summer climate predictions is minimal, but our study illustrates that improvements in seasonal forecast skill of summer climate anomalies could immediately be applied to water demand forecasts.

This study has not resolved the question of which climate variables are the optimum predictors for municipal water demand. Regression models derived from other precipitation or temperature-related variables (not shown) yielded results comparable to the models listed in Table 2. Given comparable results, we advocate the use of monthly mean temperature and precipitation, given the widespread availability of these data at many sites. Operational climate forecasts are focused on monthly mean temperature and precipitation, providing another reason to incorporate those climate variables (rather than, e.g., evaporation rate or number of days of precipitation) into water demand models.

More comprehensive demand models can build on these results by incorporating socioeconomic variables. Complementary models of the price elasticity of water demand should take climatic effects into account. With additional research, it should be possible to begin integrating economic models with climate models to address pressing concerns over management of water.

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