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Analysis of Water Use Trends in the United States: 1950 – 1995

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EXECUTIVE SUMMARY

Study Purpose

This study represents an effort to explain the key factors that have influenced water use in the United States since 1950. It seeks to provide important insights into the effects of individual factors that have influenced historical water withdrawals and uses, and to quantify the impacts of these influences over time. The principal data source for this study is the set of national water use reports that have been prepared by the United States Geological Survey (USGS) in five-year increments beginning in 1950. This historical census of national and state-level water withdrawals conducted under the National Water Use Information Program (NWUIP) of the USGS is a unique collection of data from which to study the changing role of water resources in a changing society.

Data and Methods

Estimation of total water use in the United States focuses primarily on total water withdrawals, which include the annual extractions of both fresh water and saline water, with separate estimates of withdrawals from surface water and groundwater sources. Estimates of total withdrawals are based upon the aggregation of point withdrawals for various water uses reported at the state level, and since 1985, also at the county level. Although the structure of the water use inventories has changed over time, in general, eight categories of water use (or sectors) are identified: public supply, commercial, industrial, irrigation, thermoelectric generation, rural domestic, livestock, and mining. The reported withdrawals from these sectoral uses served as the dependent variables in the modeling analysis presented in this report. The focus of the analysis is the lower 48 states, from 1950 to 1995, with a more extensive analysis of available data for the 1985 to 1995 period.

A large number of potential explanatory variables were identified through a review of the literature, suggestions from USGS staff members, and the experience of the principal investigators. Whenever possible, the data used in the specification of independent variables were obtained from sources that were readily accessible, historically consistent, and available for every state. The primary analytical approach in this study was to explore the relationship between water withdrawal data and potential explanatory variables using ordinary least squares (OLS) regression. State level models using all candidate variables were tested for the four major withdrawal categories. These models were assessed in both linear and logarithmic (log-linear) form. Simple models of long-term trends and multiple-variable explanatory and predictive models were estimated using both state-level and county-level data.

A “two-step” procedure was employed for estimating “predictive” models based on the 1985-1995 data (Chapter 6). In the first step, a “structural” model of water withdrawals (or use) was developed using key explanatory variables that had been identified from previous studies and trend analysis (Chapter 5). In the second step, the residuals from the structural models were regressed on 48 variables designating individual states using a stepwise variable selection procedure. The results were combined and displayed in a tabular form as a two-step model. The two-step model was verified by estimating a model where all structural variables are entered first followed by a stepwise selection of significant binary state indicator variables. Through this procedure, the predictive models leveraged the explanatory capabilities of the structural model with information contained in state specific residuals to minimize prediction errors. A similar estimation procedure was employed in estimating predictive models of water withdrawals using county-level data.

National and State Trends

During the 45-year period from 1950 to 1995, estimated total water withdrawals have increased from 180 billion gallons per day (bgd) to 402 bgd. The most distinctive feature of this trend was the continuous growth of withdrawals to a peak of 440 bgd in 1980, followed by a decline and flattening out of withdrawals since that time. According to predictions generated in this study, the 2000 total withdrawals are expected to be 387 bgd thus signifying continuation of the post-1980 trend of declining withdrawals. Total withdrawals (for all uses) per person followed a similar trend, peaking in 1980, and then declining steadily since that time.

Historical changes in withdrawals in the four major water use sectors each contributed differently to the trend in total withdrawals. Reported domestic withdrawals increased in every reporting period, nearly tripling between 1950 and 1995. During the same time period, total population increased only by 77 percent, resulting in increasing per-capita withdrawals for this sector. Self-supplied industrial withdrawals increased between 1950 and 1970, but have steadily declined after 1970. When compared with the total employment in manufacturing, per-employee withdrawals remained relatively stable between 1950 and 1980, then declined by nearly 30 percent in the 1985 inventory, and have changed little since that time. Trends in the irrigation sector mirror changes in total withdrawals, peaking at 150 bgd in 1980 then declining to approximately 135 bgd in the last three reporting periods. Withdrawals per acre of irrigated land peaked in 1975, and have declined slightly but steadily since that time. Thermoelectric withdrawals also follow the general trend, peaking in 1980 at 210 bgd, and changing little since that time. However, per unit use in the thermoelectric sector (i.e., gallons/kWh) has declined by nearly 60 percent since 1950, including a greater than 30 percent drop since 1980.

The 1950-1995 changes in state-level withdrawals have also contributed differently to national trends. The ten states with the largest withdrawals accounted for nearly 50 percent of all withdrawals in 1995, with two states, California and Texas, together accounting for nearly 20 percent. Total water withdrawals in the lower 48 states increased by approximately 50 percent from 1960 to 1995, even though there was a decrease in withdrawals in eight states. Fourteen states increased withdrawals by more than 100 percent; four by more than 400 percent. The states with the largest total increases were Texas (12 bgd), California (11 bgd) and Florida (11 bgd). Thirty states increased their total withdrawals by more than 1 bgd; and two of the eight states with declines showed decreases of more than 1 bgd: Ohio (1.5 bgd) and Pennsylvania (3.3 bgd).

More recently, between 1980 and 1995, several states accounted for the majority of the increase in withdrawals. Texas, Illinois, Wyoming, Arkansas, and Wisconsin accounted for nearly 75 percent of the increase in total withdrawals, with Texas outpacing all other states with an increase of more than 9 bgd. Twelve states had reductions in withdrawals greater than 2 bgd during this period, accounting for nearly 80 percent of the total reductions. Reductions in the top four states (California, Pennsylvania, Indiana, New Jersey) totaled nearly 24 bgd.

Demand Drivers and Intensity of Use

Population, employment, irrigated area, and power generation were selected to represent the main drivers of water use. Water use was expected to change with changes in the values of these drivers. However, total withdrawals also depend on the intensity of water use per unit of activity represented by each driver. Table ES.1 shows the allocation of the historical (1950 to 1995) change in total withdrawals by category of water use into the effects that can be attributed to changes in water demand drivers and those related to changes in per unit use.

Table ES.1 Components of the 1950-1995 Changes in Sectoral Withdrawals

Component Effect	Pre -1980 Effect (in mgd)	Percent of Pre -1980 Effect (%)	Post-1980 Effect (in mgd)	Percent of Post-1980 Effect (%)
Public-Supply Withdrawals				
Growth in total population	+6,681	36	+5,103	67
Increase in per capita use	+8,848	48	+945	13
Net increase in population served	+2,950	16	+1,540	20
Total effect	+18,479	100	+7,588	100
Industrial Withdrawals				
Employment growth (decline)	+1,755	187	-5,809	-38
Declining per employee use	-5,472	-87	-9,663	-62
Total effect	-3,697	100	-15,472	-100
Irrigation Withdrawals (in 1,000 ac. ft./year)				
Growth in irrigated acreage	+106,929	131	+2,241	+11
Declining per acre use	-25,583	-31	-21,976	-111
Total effect	+81,386	100	-19,735	-100
Thermoelectric Withdrawals				
Growth in thermoelectric generation	+214,022	208	+71,141	+384
Declining use per unit	-110,918	-108	-89,656	-484
Total effect	+103,104	100	-18,515	-100

The allocation of the total pre-1980 change in public supply withdrawals shown in Table ES.1 is based on three straightforward assumptions. First, the effect of growth in total population between 1950 and 1980 is calculated by multiplying the 1950-1980 increase in total population by the mean per capita usage in 1950. The resultant value of 6,681 mgd represents the change in withdrawals when the gross per capita use is held constant. Second, the 1950-1980 effect of the increase in per capita use is calculated by multiplying total population served in 1980 by the increase in publicly-served per capita rates between 1950 and 1980. The resultant value of 8,848 mgd represents a net increase in publicly-served use due to increasing per capita usage rates. Finally, the third effect, namely that associated with the increase in the proportion of population served is distinguishable when public supply withdrawals are compared to total population. The value of 2,950 mgd represents an increase in withdrawals that can be attributed to the extension of service areas of public water supply systems to reach greater percentage of total population. The sum of the three effects is equal to the 1950-1980 increase in public supply withdrawals reported in the USGS circulars. The next column of Table ES.1 shows the percent contribution of each effect, and indicates that the largest part of the 1950-1980 increase in withdrawals (48 percent) can be attributed to increases in per capita rates. The growth in total population accounted for 36 percent of the increase and growth in coverage of public water supply systems for 16 percent. A similar analysis was performed for the 1980-1995 changes in public supply withdrawals and those in each of the other water use sectors.

An important finding presented in Table ES.1 is that in the industrial, irrigation and thermoelectric sectors, declining rates of withdrawals per unit measure of respective drivers controlled the growth in withdrawals between 1950 and 1980 and accounted for a major part of the 1980-1995 declines. In absence of the declining per-unit rates of withdrawals, total withdrawals would be 142 bgd (32 percent) higher in 1980 and 263 bgd (65 percent) higher in 1995.

Determinants of Changes in Per Unit Use

A multiple regression approach was used to identify and estimate the contribution of various factors to the historical changes in per-unit withdrawals. Table ES.2 shows the estimated contributions of specific explanatory variables to the total change in per capita, per employee, per acre and per kilowatt-hour withdrawals between the beginning and end of the reporting period. These individual effects are calculated using the estimated regression coefficients and changes in mean historical values of key explanatory variables.

In the public supply sector, the largest impact on per capita use can be attributed to the historical growth in median family income (inflation adjusted). Given the historical increase and using the estimated elasticity of income of +0.249, the effect on per capita use is +41.1 gpcd or approximately 69 percent of historical (1950-1995) increase in per capita use. Changes in two other variables also contributed to the increase in per capita use. These are the change in percent of urban population (+20.6 gpcd) and change in the proportion of mobile homes in the national housing stock (+16.2 gpcd). The former is related to income and the latter is likely a result of the fact that mobile homes generally do not have water meters while having all modern water-using appliances. Changes in two other variables, namely population density and percent of population connected to public systems had a significant negative effect on per capita public-supply withdrawals.

Table ES.2 Effects of Historical Changes in Explanatory Variables on Per Unit Water Withdrawals at State Level from Log-Linear Regression Models

Explanatory Variable	Variable Elasticity or Coefficient	Effect of Change in Variable Values on Per Unit Use	Percent of Total Effect
Per Capita Public-Supply Withdrawals			
Median family income	+0.249	+41.1	+69.3
Population density	-0.085	-5.9	-9.8
Percent of urban population	+0.013	+20.6	+34.5
Percent of population served	-0.841	-13.8	-23.2
Percent of mobile homes	+0.016	+16.2	+27.1
Other variables	--	+1.2	+2.0
Per Employee Industrial Withdrawals			
Chemical and allied products (SIC28) emp. share	+0.081	-15.3	+2.3
Lumber and wood products (SIC24) emp. share	+0.034	+26.1	-4.0
Primary metal industries (SIC33) emp. share	+0.048	-372.0	+56.9
Food and kindred products (SIC20) emp. share	+0.024	-90.3	+13.8
Percent of groundwater withdrawals	-0.006	-87.4	+13.4
Percent of saline water withdrawals	+0.005	-70.1	+10.7
Other variables	--	-45.1	+6.2
Gross Irrigation Depth (Western States)			
Summer season precipitation	-0.209	+0.1	+6.0
Total state irrigated acreage	+0.244	+1.6	+86.4
Percent of withdrawal from surface source	+0.009	+0.7	+38.0
Minimum PDSI	-0.026	-0.6	-30.4
Unit Thermoelectric Withdrawals (Group 1)			
Percent of thermo. generation from fuels	+0.005	-1.43	+4.9
Percent of installed capacity utilized	-0.021	+5.64	-19.3
Trend (long-term, not attributed)	-0.023	-33.45	+114.4
Unit Thermoelectric Withdrawals (Group 2)			
Percent of thermoel. gen. from fuels	+0.027	-1.4	+13.2
Percent of installed capacity utilized	+0.013	+1.2	-11.3
Trend (long-term, not attributed)	-0.046	-10.4	+98.1

In the industrial sector, the declining employment in the primary metal industries (SIC 33) had the largest impact on per employee water use. In irrigation, the historical change in gross irrigation depth (in inches per year) was minor in the western states. A decrease of 5.1 inches/year in the eastern states could not be clearly attributed to an explanatory variable, except for the percent of irrigated land in rice. Similarly, the major historical declines in thermoelectric withdrawals per kilowatt-hour of generation could not be attributed to any of the explanatory variables. One of the most likely explanatory variables for the changes in thermoelectric withdrawals, the proportion of generating capacity which utilizes close-loop cooling (i.e., cooling towers), could not be thoroughly investigated because the data are not available prior to the 1990 inventory.

Structure of Water Use Models

Extensive multiple regression analysis was performed on withdrawal data for 1985, 1990 and 1995 (Chapter 6). The analysis focused on identifying explanatory models of water withdrawals or use and on building predictive models. The findings of these analyses are summarized by presenting the elasticities of key explanatory variables obtained from regression models of per-unit use. Table ES.3 compares the estimated elasticities for each category of water use. Because the magnitude of estimates varied depending on model specification, a range of values is presented. The last column of Table ES.3 shows the elasticity in the predictive model, which was used in generating predictions for 1980 and 2000.

Table ES.3 Elasticities of Key Explanatory Variables in Log-Linear Regression Models

Use-category/ Explanatory Variable	Low Value	High Value	Used in Prediction
Per Capita Public-Supply Withdrawals			
Gross State Product per capita	0.138	0.142	0.138
Average price of water- municipal	-0.075	-0.184	-0.075
Total summer precipitation	-0.122	-0.194	-0.122
Average summer temperature	0.441	0.799	0.799
Per Employee Industrial Withdrawals			
SIC24 share of manuf. empl.	0.091	0.095	0.091
SIC26 share of manuf. empl.	0.303	1.003	1.003
SIC28 share of manuf. empl.	0.406	0.536	0.500
SIC33 share of manuf. empl.	0.192	0.326	0.192
Average price of water - industrial	-0.161	-0.297	-0.297
Average summer temperature	1.199	1.894	1.437
Percent of self-supplied withdrawals	1.484	1.897	1.632
Irrigation Depth (Western States)			
Percent of conveyance losses	0.123	3.836	0.123
Total summer precipitation	-0.121	-1.608	-0.121
Minimum PDSI index	-0.038	0.049	-0.038
Irrigation Depth (Eastern States)			
Percent of area using surface methods	0.648	5.401	0.648
Agricultural services GSP per acre	0.083	0.101	0.101
Total summer precipitation	-0.276	-0.897	-0.897
Minimum PDSI index	0.049	0.082	0.082
Unit Thermoelectric Withdrawals			
Percent of installed capacity utilized	-0.707	-0.752	-0.752
Percent of installed cap. w/cooling towers	-0.270	-0.270	-0.270
Percent of fuel/gas steam gen. units w/cool. tower	-0.117	-0.128	-0.128
Percent of total steam cool. cap. using fuel/gas	0.067	0.100	0.067
Cooling degree days	-0.137	-0.286	-0.189

The elasticity of public-supply withdrawals with respect to income (measured as gross state product per capita) is +0.138. Elasticities of price ranged from –0.075 to –0.184. Elasticities of the two weather variables ranged from –0.122 to –0.194 for precipitation and from +0.441 to +0.799 for temperature. High elasticities of precipitation were obtained for irrigation use. Elasticity of average price in industrial sector ranged –0.161 to –0.297, which indicates more elastic demand than that of public supply. It is important to note that the causality of some variables in Table ES.3 is difficult to ascertain. It is likely that some variables served only as proxy measures for variables that were not included in the regression models.

Accuracy of State-level Predictions

Out-of-sample predictions for the 1980 (Note: 1980 data year were not used in model estimation) were used to test the accuracy of predictive models. Table ES.4 shows the mean absolute percentage error for predictions for the lower 48 states. Also shown is the number of actual 1980 state withdrawal values that were within the 90- and 95-percent confidence intervals associated with the predictions.

Table ES.4 Accuracy of In-sample (1985-1995) and Out-of-sample (1980) Predictions of State Total Withdrawals

Use Category	1985-1995 Mean Absolute Prediction Error (%)	1980 Mean Absolute Prediction Error (%)	No. of 48 Obs. Falling within 90% interval	No. of 48 Obs. Falling within 95% interval
Per capita public-supply withdrawals	6.0	12.4	11	19
Per employee industrial withdrawals	20.1	44.0	16	20
Irrigation depth (Western States)	8.0	20.5	3	3
Irrigation depth (Eastern States)	22.0	51.9	10	10
Per kWh thermoelectric withdrawals	17.9	581.8*	11	13

** The large absolute prediction error is caused by a data outlier Washington 1980.*

The predictions for 1980 represent a "worst case" scenario for model testing because the models were estimated using the post-1980 data which reported major declines in withdrawals. The error of in-sample predictions ranged from 6.0 percent for public supply to 22.0 percent for irrigation in the West. The error of 1980 predictions of public supply and western irrigation withdrawals was approximately 20 percent. It was close to 50 percent for industrial and eastern irrigation withdrawals. An error of similar magnitude is obtained for thermoelectric withdrawals when the prediction for one state (Washington) is removed.

The models in this study were also used to make predictions for the year 2000 withdrawals. The 2000 predictions were obtained by multiplying the predicted per unit withdrawals for each state by the value of the driver (population served, employment, irrigated area and thermoelectric generation) in 2000. The year 2000 predictions are compared to the 1995 reported withdrawals in Table ES.5.

Table ES.5 Comparison of 1995 Estimates and 2000 Predictions

Use Category	Reported 1995 Withdrawals (in mgd)	Predicted 2000 Withdrawals (in mgd)	Percent Change 1995-2000 (%)
Public supply	39,485	45,446	15.1
Industrial	22,290	19,323	-13.3
Irrigation	132,954	138,768	4.4
Thermoelectric	185,931	168,149	-9.6
Rural domestic	3,360	3,259	-3.0
Mining	3,629	2,353	-35.2
Livestock	5,472	5,922	8.2
Total	393,121	383,220	-2.5

Totals do not include D.C., Hawaii, Puerto Rico, and Virgin Islands.

County-level Data and Models

Multiple regression models were also developed using the county-level data for 1985, 1990 and 1995. Both national and state-specific models (for 2 eastern and 2 western states) were estimated. Relatively small absolute percentage errors of in-sample predictions were obtained from models which were developed for specific states (i.e., regressions estimated from county-level data from a given states). The state-specific models obtained for counties of a given state have errors that are less than one-half of the average size of errors, which were obtained from national models (i.e., regressions estimated from available data for counties in the lower 48 states). The relative prediction errors are compared in Table ES.6

Table ES.6 In-sample Prediction Errors of Log-Linear County-Level Models

National/ State Model	Public Supply		Industrial		Irrigation	
	MAPE 1 (%)**	MAPE 2 (%)***	MAPE 1 (%)	MAPE 2 (%)	MAPE 1 (%)	MAPE 2 (%)
National model*	33	--	>1000	-	139	--
National model*	--	--	--	--	48	--
Arkansas model	13	34	47	>1000	29	100
North Carolina model	26	38	70	>1000	58	108
Kansas model	9	22	40	394	15	35
Oregon model	14	36	44	275	15	23

*Separate national models were estimated for irrigation in eastern and western states
** MAPE 1 is the mean absolute percent error in prediction from state specific models.
*** MAPE 2 is the mean absolute percent error of prediction results for sample states extracted from model of all U.S. counties.

Relative prediction errors for county-level withdrawals are generally higher than errors in state-level predictions. However, the absolute errors measured by root mean square error are significantly smaller. This suggests that improved predictions can be achieved by state-specific modeling of county-level withdrawals and use.

Recommendations

Based on the results of this study, the following recommendations are proposed for developing aggregate models for the estimation of national, state, and county-level aggregate water withdrawals:

1. The modeled variable should be "water withdrawals per unit" such as per capita, per employee, per irrigated acre, or per kilowatt-hour. Total water withdrawals can be calculated by multiplying the model-estimated unit usage rates for each category by the number of units (i.e., the demand driver) such as persons, employees, acres or kilowatt-hours. Log-linear models with such dependent variables offer the highest accuracy.

2. Predictive models should include both the standard explanatory variables and indicator variables for individual states or counties to capture their "unique" local water-use characteristics, as well as any statistically significant state- and county-specific trends in usage over time.

3. Water withdrawals by source can be estimated by allocating total withdrawals among the alternative sources. The proportions of withdrawals from each type of source vary considerably between states but are generally "conservative" within individual states or counties.

The main conclusion of this study is that the development of accurate models of water withdrawals for the U.S., individual states, and counties is possible. The data on water withdrawals and use that have been collected under the National Water Use Information Program (NWUIP) offer an excellent opportunity for advancing the "science of water use" and for developing statistical predictive models that can be helpful in QA/QC process for future national compilations and estimates of water use, especially in non-reporting states or counties. The predictive models can also be used for long-term predictions of water use at the state and national levels.