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Lack of influence of climate on present cost of water supply in the USA

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Abstract

Previous studies have sought to develop econometric models of water supply systems, which can be used to predict future water supply costs; none, however, have investigated the influence of climatic factors. In this paper, climatic and other regional influences on the costs of water supply in the USA are explored using multivariate analysis of water supply costs from water supply utilities located throughout the USA. Results showed that over 90% of the variation in present water supply capital and operating costs for surface and ground water systems can be explained by variations in quantity of water delivered, with other variables, particularly regional climate, playing a negligible role. An analysis of the historic development of water supply in the USA showed that capital expenses for water supply systems are a relatively small component of the present total annual costs because: (1) the original capital expenditures were reduced for utilities due to large public subsidization; (2) repayment of capital expenditures is now complete owing to the long time period since the original investments; and (3) new policies encourage demand management instead of supply expansion. Therefore, the present costs of water supply are not related to climate and thus are not a useful guide to future costs in studies that evaluate climate change impacts.

Keywords: Climate; Climate change; Cost; Regression; United States; Water supply

1. Introduction

In the 1970s and 1980s many studies focused on the cost of public water supply in the Unite States because of the passage of the Safe Drinking Water Act (SDWA, Public Law 93–523) i 1974, which provided drinking water guidelines and encouraged researchers to examine factor responsible for the cost of water supply. Public supplies are defined by Solley *et al.* (1993) as "wate withdrawn by public and private suppliers and delivered to multiple users for domestic commercial, industrial and thermoelectric power uses" (page 20). In the 1990s, researchers onc again began examining the costs of water supply systems largely owing to the possible influence o global warming-induced climate change upon system costs in the long-term future. In this pape we examine the correlation between climate and the present cost of public water supply across th USA. Such information may be useful in estimating future costs under climate change as well a for managing present systems.

Like other researchers, we define water supply cost as that paid by the user of the water. It ma not reflect the value of the water to the users or, as is shown here, the actual cost of supply. Th cost data also does not include the cost of wastewater management. Since many water users pa for their wastewater management based upon their water use, the addition of wastewater costs t water supply costs may have better reflected the actual costs to the consumer for water supply. W searched for databases of wastewater costs, but none were extensive as, or compatible with, th large databases of water supply costs employed here.

Clark did much of the early work in the 1970s and 1980s on water supply costs. In a series o papers, he and colleagues: (1) suggested that different cost functions can be derived for eac system component and that the cost of support services dominated the total operating and capita costs of water supply (Clark, 1976; Clark *et al.*, 1979); (2) evaluated the economic impact of th SDWA regulations (Clark *et al.*, 1979); (3) performed regression analysis to estimate the tota cost of 23 small systems as a function of quantity of water supplied (Stevie *et al.*, 1979); and (4 determined how to optimize economically the size of a utility based upon cost minimizatio (Clark & Stevie, 1981a, 1981b). With the exception of Stevie *et al.* (1979), the above researc was based upon only 12 utilities having revenues greater than US$500,000 during the perio 1965–1974 with at least one utility within each of the ten US Environmental Protection Agency (US EPA) regions. None of these studies included any climate variables in the analyses and, no unexpectedly, the variable which explained most of the variability in costs was always the quantity of water supplied.

Later work on water supply costs focused on the efficiencies of publicly owned and privately owned water supply systems. By fitting generalized cost models (primarily translog cost functions) to both regional and national data sets of utility costs, Feigenbaum & Teeples (1983), Teeples *et al.* (1986) and Teeples & Glyer (1987) could not find definitive cost differences between the two types of ownership. Again, no climate variables were introduced or tested in these analyses.

Male *et al.* (1991) performed an analysis of the 1987 National Association of Water Companies (NAWC) database representing 143 private companies located throughout the United States. They developed a generalized cost model without climate variables and found that total cost increases as quantity increases and decreases as the quantity of water per connection increases.

The US EPA (Hertzler & Davies, 1997) developed capital cost curves of the individual components of water supply systems to estimate the local and national costs to comply with the SDWA and amendments. The only influence of climate on their analyses was on the costs of transmission and distribution systems, because in colder climates pipes must be placed deeper to avoid frost damage.

In this paper, we report upon research that relates the costs of water supplies throughout the USA to the regional climates of the service areas. Climatic regimes in the USA range from arid with annual runoff as low as 5 mm/year to humid with annual runoff as high as 2,500 mm/year. Present costs might be sensitive to the regional climate because Clark *et al.* (1979) report that 67% of capital costs of USA public water systems are related to collection, transmission and distribution costs. Thus the costs of public water supply systems may be more expensive in arid than in humid areas because water must be collected and transported from more sources and longer distances in arid areas than humid areas.

2. Methodology

Our primary goal was to investigate the possible influence of climate on the present costs of USA public water supply. We assumed a log–log functional form of a water supply cost model similar to that of Clark & Stevie (1981a) and Male *et al.* (1991). The response variable was the cost of public water supply, and climatic and other explanatory variables were considered as predictor variables. We analyzed other economic, hydrologic and infrastructure variables in addition to climatic ones so we could determine the importance of climatic variables in relation to other variables. We took the natural logarithms of the data and then performed ordinary least squares regression to fit multivariate linear equations of the form:

$$y = \ln \beta_0 + \beta_1 \ln x_1 + \beta_2 \ln x_2 + \ldots + \beta_k \ln x_k + \varepsilon \qquad (1)$$

where y is the logarithm of the response variable (cost), ln (β_0) is the intercept, β_1 is slope coefficient for the first explanatory variable, β_k is slope coefficient of the kth explanatory variable and ε is random model error. Model error ε is assumed to have zero mean, constant variance and to follow a normal distribution. Equation (1) can be rewritten (for the response variable cost) in the form:

$$\text{Cost} = \beta_o x_1^{\beta_1} x_2^{\beta_2} \ldots x_k^{\beta_k} \qquad (2)$$

Stepwise regression procedures were used to select appropriate independent variables. Models were screened to assure that all model parameters were significantly different from zero and model residuals were independent, had zero mean, constant variance and were approximately normally distributed. Variance inflation factors were computed to test for multicollinearity (i.e. correlation) among the explanatory variables (Helsel & Hirsch, 1992). Standard influence statistics were used to identify and remove observations that strongly influenced the regression model parameters (Helsel & Hirsch, 1992).

3. Cost of water supply

In 1995, the US EPA conducted a survey of public water systems (US EPA, 1997a, 1997b, 1997c) by distributing a questionnaire to a random sample of 3,658 water supply systems. Included in the large set of information were 1995 total expenses including operating costs, capital investment costs and taxes, and quantities of water delivered. Even if a water supply utility provided wastewater treatment, no costs for wastewater treatment were included in the data.

Following quality assurance testing, the size of the database provided to us by the US EPA was reduced to 1,980 systems. These systems were located by the postal or zip code of their service area. Several systems were further eliminated for one or more of the following reasons: (1) no zip code provided; (2) outside continental USA; and (3) no reported value greater than zero for either total expense or quantity delivered. The total number of systems included in the initial regression analysis was 1,363 of which 246 systems relied 100% on surface water sources and 618 systems relied 100% on ground water sources. Figure 1 illustrates that the systems were evenly distributed throughout the continental United States. It also shows the 18 watershed or hydrologic regions

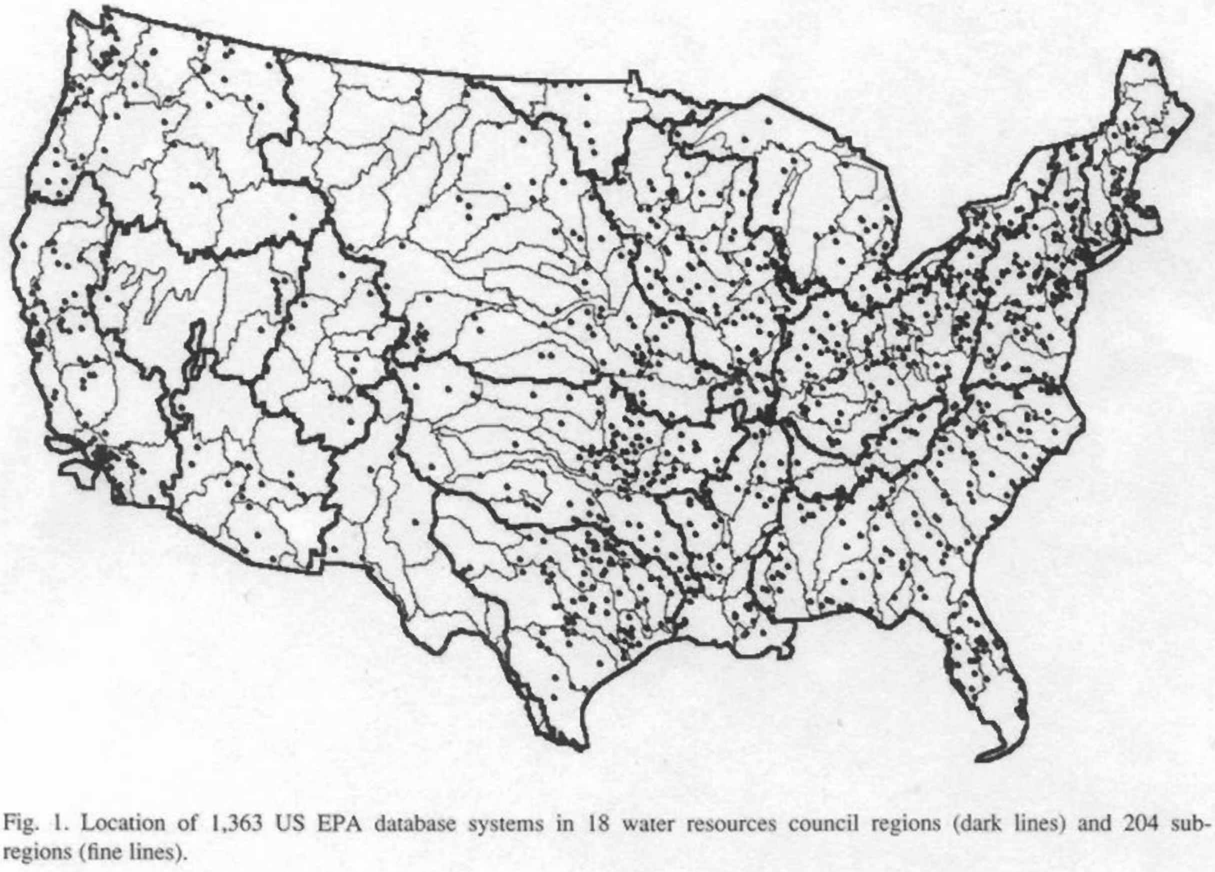

Fig. 1. Location of 1,363 US EPA database systems in 18 water resources council regions (dark lines) and 204 sub-regions (fine lines).

and the smaller 204 sub-regions used by the United States Water Resources Council (1970) and in this study for the purposes of water resources analysis.

The response variable used in our cost regressions was the total annual expense. To investigate the relative influence of climate on the cost of water supply, five categories of explanatory variables were used: (1) system operating; (2) climatic; (3) hydrologic; (4) infrastructure; and (5) economic. They are described below.

3.1 System operating variables

Quantity is defined as the revenue-producing water (referred to as quantity delivered or sold), which equals the quantity produced minus the amount required for public uses or lost in the system.

3.2 Climatic variables

Annual precipitation and temperature. The mean areal annual precipitation and temperature were calculated for each of the 204 sub-regions in Figure 1, using a geographic information system (GIS) and the 2.5 minute digital maps of mean annual precipitation and temperature developed using the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al.*, 1994). These digital climate grids are based upon information from 9500 stations in the USA over the period 1961–1990. Each of the 1,363 public water supply systems was assigned the mean annual precipitation and temperature of their hydrologic subregion.

3.3 Hydrologic variables

Streamflow. The mean and variance of annual streamflow were estimated for each of the 204 sub-regions using regression equations developed by Vogel *et al.* (1999) that related these variables to the hydrologic, geomorphic and climatic conditions of watersheds. These estimates were assumed to apply to the public water supply systems within each sub-region.

Other water withdrawals. It was hypothesized that the cost of water supply in a region might be influenced by the magnitudes of other water withdrawals in the region, as they might limit supply. Total fresh water withdrawals, surface water withdrawals and ground water withdrawals for public supplies in 1995 in each of the 204 sub-regions were taken from USGS National Water-Use Data Archive (1998).

Baseflow index. Baseflow index is the ratio of the baseflow (defined as ground water outflow contributing to runoff in rivers during dry conditions) to the mean annual streamflow. Baseflow in each of the 204 sub-regions was based upon regression equations developed by Larsen (1998) relating baseflow to hydrologic, geomorphic and climatic characteristics of basins across the USA.

Aridity. Aridity is defined as the dimensionless ratio of annual evapotranspiration to annual rainfall computed using:

$$\text{Aridity} = \frac{\overline{E}}{\overline{P}} = \frac{\overline{P} - \overline{Q}}{\overline{P}} \tag{3}$$

for each of the 204 sub-regions. Here $\overline{E}$, $\overline{P}$ and $\overline{Q}$ are the estimates of the long term mean evapotranspiration, precipitation and streamflow for each basin.

3.4 Infrastructure variables

Reservoir storage was estimated from the normal storage—defined as "the total storage capacity in a surface water reservoir below the normal retention level, including dead and inactive storage and excluding any flood control surcharge storage" (Federal Emergency Management Agency, 1996). The amount of reservoir storage within each of the 204 sub-regions was calculated based upon the National Inventory of Dams database (Federal Emergency Management Agency, 1996). This database comprises 75,187 dams and was disaggregated to select only reservoirs that are within the continental USA, provide some water supply storage and have a reported value for normal storage. If normal storage was not reported, it was estimated by an equation developed by Lane (1998) that relates storage to reservoir surface area. A total of 7,578 dams remained after the elimination process, and the normal storage of all dams within each of the 204 sub-regions was summed.

3.5 Economic variables

Cost of electricity. The cost of electricity for pumping may vary regionally. Therefore. variations in the costs were considered by assigning to each water supply system the electricity cost in its state from US DOE (1998).

Construction costs. To account for possible variations in construction costs, each system was assigned the cost index of the closest city in its state from the Means Heavy Construction Cost Data (Smit, 1992).

4. Results of public water supply cost regression analyses

Multivariate regression analyses were conducted for three categories of public water supply system: all systems, 100% surface water systems and 100% ground water systems. No effort was put forth to distinguish between publicly or privately owned systems because Feigenbaum & Teeples (1983), Teeples *et al.* (1986) and Teeples & Glyer (1987) did not find definitive cos differences between the two types of ownership. Using stepwise regression procedures, the only significant explanatory variable found for each of the three categories of systems was the quantity of water delivered, resulting in the model:

$$\text{Total expense} = aQ^b \qquad (4$$

where total annual expense is in US dollars in 1995, Q is quantity of water delivered in cubic meters per second ($m^3\ s^{-1}$) and ln a and b are the estimated model parameters reported in Table 1 Table 1 describes the models for all systems, 100% surface water and 100% ground water. None of the other hydrologic, infrastructure or climate explanatory variables considered explained a significant amount of the models' uncertainty. The parameters for each model in Table 1 are similar with parameter ln a varying from 16.4 to 16.5 and parameter b varying from 0.839 to 0.914. Table 1 also reports the goodness-of-fit statistics R^2 (adjusted for number of mode

Table 1: Summary of total expense equations for EPA water supply cost analysis (equation 4).

System category	Number of systems	Model	ln (*a*)	*b*	R^2 (%)	*SE* (%)
Total systems	1302	Coefficient *t*-Ratio	16.5 482.76	0.896 129.14	92.8	69.1
100% surface water systems	232	Coefficient *t*-Ratio	16.4 260.76	0.839 57.32	93.4	62.6
100% ground water systems	591	Coefficient *t*-Ratio	16.4 268.23	0.914 79.30	91.4	71.4

parameters) and % standard error SE (computed using)

$$SE = \sqrt{\exp\left(s^2(1+p/n)\right)-1}$$

where s^2 is the variance of the model residuals, p is the number of model parameters and n is the number of samples. Interestingly, Table 1 documents that the quantity of water delivered, alone explains over 91% of the variability in the total annual costs of all systems, as well as for only surface and ground water supply systems. The overall goodness-of-fit of the model for all systems is shown in Figure 2; similar plots were found for the cases when only surface and ground water systems are considered.

We further reasoned that climate may only influence the cost of stressed water supply systems. Stressed systems are defined as those in regions with high withdrawals relative to natural streamflows and ground water baseflows and identified using the four stress indicators summarized in Table 2. These dimensionless ratios were calculated for the 204 USGS sub-regions and then only those stressed water supply systems were analyzed using multivariate analysis. Again, we found that quantity delivered was the only variable providing significant explanatory power. Futhermore, the parameters of the individual models for each of the four

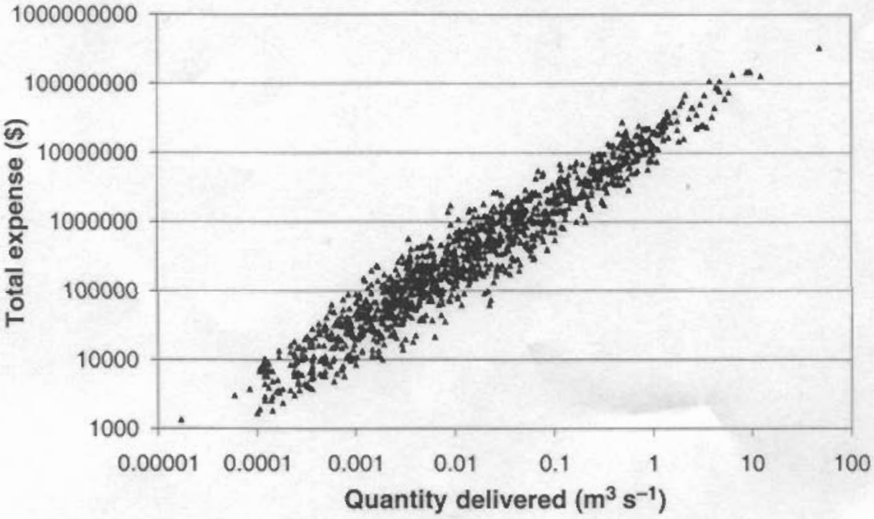

Fig. 2. Total annual expenses and quantity delivered of water supply systems in EPA database.

Table 2: Summary of stress indicators and cutoff criteria for EPA water supply analysis.

System category	Stress indicator	Cutoff criteria	Reason for criteria selection
100% surface water systems	Normal storage/surface water withdrawal	> 1	More storage per withdrawal reflects vulnerability to drought
100% ground water systems	Ground water withdrawal/baseflow	> 1	More withdrawal than supply replenishment reflects excessive pumping
Total systems	Total water withdrawal/mean annual streamflow	> 1	Consistent with surface and ground water cutoff criteria
Total systems	Total water withdrawal/mean annual streamflow	> 0.5	More stringent cutoff for sustainable withdrawal rates

stressed conditions were nearly identical to the parameters in the models in Table 1. Therefore this analysis suggested that climate and other regional variables are not significantly related to costs of present water supply, even under stressed conditions.

We performed the same type of multivariate analysis with the water supply system database of the National Association of Water Companies (NAWC, 1997). The NAWC is an organization of investor-owned water utilities (i.e. private systems) with gross revenues over US$1 million. Cost data reported include annual total costs as well as operating costs by component: production, purification, transmission/distribution, accounting/administrative and total.

The year 1993 was selected since this year contained information for the largest number of systems (i.e. 104). The systems were located by the zip code reported in their mailing address. Systems were eliminated if they were outside continental USA or had no reported costs or quantity sold information. This elimination reduced the total number of systems to 90. The systems were not evenly distributed across the USA; rather, the majority of the systems were located in the east-central USA, along the mid-Atlantic coast, or in the northeast with a few systems in the southern and western USA.

The NAWC data analysis also documented that quantity of water delivered was the best single predictor of total annual cost with model parameters similar to those found earlier using the US EPA database. Regression analysis of the annual operating costs reported by the NAWC indicated that total or component operating costs were not significantly related to the climatic variables.

Figure 3 plots the annual accounting/administrative expenses, total annual operating expenses and total annual expenses of the NAWC utilities versus delivered water. This illustration shows that accounting/administration expenses account for approximately one third of the total operating expenses. This result supports the findings of Clark *et al.* (1979) who found that support services are approximately 31% of operating costs. Operating and capital expenses each appear to comprise about half of the total expenses.

5. Conclusions

We found that the present cost of water supply does not appear to be related to the climate associated with the service area. This conclusion is surprising because Clark *et al.* (1979) report

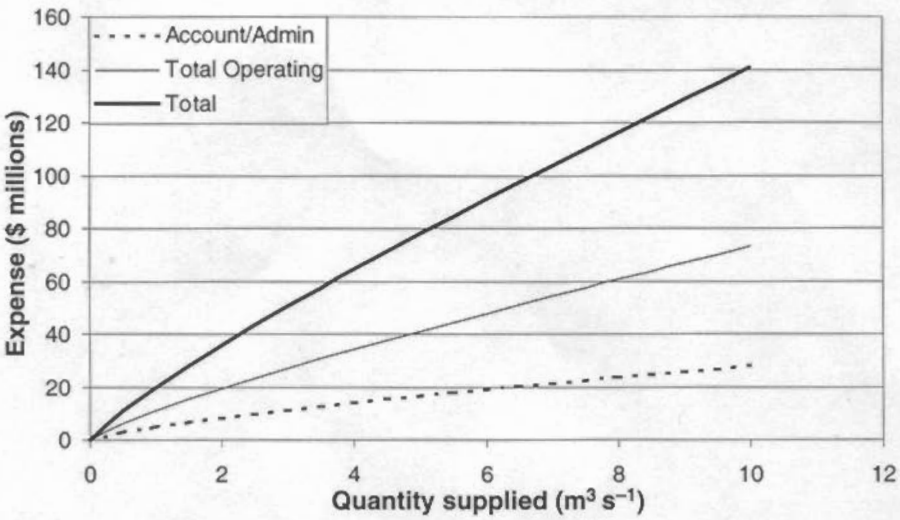

Fig. 3. Comparison of annual accounting/administrative, total operating, and total costs of NAWC systems.

that 67% of capital costs of public water systems are related to collection, transmission and distribution costs. Thus, one might expect that the costs of public water supply systems may be more expensive in arid than in humid areas because water must be collected and transported from more sources and longer distances. A possible explanation for the lack of climate sensitivity to water supply costs in the USA is offered by Rogers (1993) and by Larsen (1998) who analyzed the history of several large water supply utilities in the USA. Historically, water systems in the USA attempted to balance increases in demand with water supply expansion, until the 1970s. Bonds or other methods of public subsidization largely financed these water supply expansion projects; thus, the construction costs were generally not included in the water rates. In the 1970s, the environmental movement resulted in several legislative policies and regulations affecting water policy that limited reliance upon supply augmentation and encouraged a switch to demand management. This switch resulted in a decrease in capital investment for the most climate-sensitive water supply projects (e.g. dams, transmission systems). Therefore, capital expenses for water supply systems are a relatively small component of the present total annual costs because (1) the original capital expenditures were reduced due to large public subsidization, (2) repayment of capital expenditures is now complete owing to the long time period since the original investments, and (3) new policies encouraged demand management instead of supply expansion. Climate sensitivity is further reduced because, as we showed above, operating expenses (also insensitive to climate) comprise approximately half of the present total expenses. We conclude that owing to past institutional practices, the present costs of water supply are not related to climate and, therefore, cannot be used as a guide to future costs under changed climates. In addition, the present trend of undercharging for water supply in the USA should make the adaptation to a changed climate more difficult if the future climate leads to more water scarcity than the historical climate; users are now used to abundant water supply at relatively inexpensive prices.

Our finding also has implications for the present management of water resources in both the USA and the developing world. Our results imply that in the USA public water users are not being charged the full costs of their use of water resources. The lack of transparent costs and th consequences of the undercharging have been discussed by Rogers (1993), who state undercharging can contribute "to undervaluation, to failures to invest and to seriou misallocations among users". In addition, because the impact of full price charging on wate allocation in USA is not really known because of past subsidization and repayment and becaus of the different value of water to users in the developing world (where, for example, in some place public water availability is a matter of life or death, whereas in USA it means whether or not yo can wash your car or driveway or water your yard), USA experience with pricing may not provid guidance on how water should be charged for in the developing world.

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