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WATER USE BY THERMOELECTRIC POWER PLANTS IN THE UNITED STATES[1]

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ABSTRACT: Thermoelectric power generation is responsible for the largest annual volume of water withdrawals in the United States although it is only a distant third after irrigation and industrial sectors in consumptive use. The substantial water withdrawals by thermoelectric power plants can have significant impacts on local surface and ground water sources, especially in arid regions. However, there are few studies of the determinants of water use in thermoelectric generation. Analysis of thermoelectric water use data in existing steam thermoelectric power plants shows that there is wide variability in unitary thermoelectric water use (in cubic decimeters per 1 kWh) within and among different types of cooling systems. Multiple-regression models of unit thermoelectric water use were developed to identify significant determinants of unit thermoelectric water use. The high variability of unit usage rates indicates that there is a significant potential for water conservation in existing thermoelectric power plants.

(KEY TERMS: water conservation; water supply; statistics; thermoelectric generation; unit water use; multiple-regression)

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INTRODUCTION

Compared with many other countries, the United States is relatively well endowed with fresh water resources. However, despite this abundance, adequacy of water supply has emerged as one of America's primary resource issues mainly because of the following five reasons: (1) uncertainties as to the availability of water supplies stemming from the temporal and spatial vicissitudes of the hydrologic cycle and the threat that global warming might alter this cycle; (2) the high costs of developing additional water supply infrastructure; (3) the vulnerability of water resources and the problems of restoring and protecting valued surface and ground water resources; (4) the importance of reliable supplies of high-quality water for human and environmental health and economic development; and (5) the shortcomings of institutions for allocating scarce water supplies in response to changing supply and demand conditions (Frederick, 1995). In 2003, the U.S. General Accounting Office (GAO) was asked by Congress to assess the range and complexity of freshwater supply issues in the United States. The findings of GAO indicate that the nation's demand for water is growing, while the nation's capacity for storing surface water is limited and ground water is being depleted. The survey of state water managers shows

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that they expect freshwater shortages in the near future, and consequences may be severe. Even under normal conditions, water managers in 36 states anticipate shortages in localities, regions, or statewide in the next 10 years (General Accounting Office, 2003).

Thermoelectric power generation has significant impacts on water resources. In addition to the frequently discussed "thermal pollution" (Horvath and Brent, 1972; Mostertman, 1976; Youngbluth, 1976; Huisman *et al.*, 1980), the requirement for large volumes of water at the plant location has also become a concern. Gleick (1994) estimated that the weight of cooling water withdrawn by coal-fired plants with once-through cooling systems is approximately 12.5 times the weight of the coal burned. This massive water demand by thermoelectric power plants can have significant impacts on both surface and ground water sources in some locations, especially in regions where water resources have already been appropriated. In fact, water availability has increasingly become an important factor to be considered in the permitting and siting of thermoelectric power plants (Baum *et al.*, 2003) including permit denials on this basis (Johnson, 2001a,b; Canadian Broadcast Corporation, 2002; Morlock, 2002; Seattle Post – Intelligencer, 2002).

Water withdrawals and consumptive use of water are two important aspects of water use. Water withdrawals refer to the water withdrawn or diverted from a ground or surface water source for various uses, while consumptive use refers to the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment (Solley *et al.*, 1993). Since 1950, the US Geological Survey has been compiling national water use reports in 5-year increments (MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley *et al.*, 1983, 1988, 1993, 1998). However, the agency did not report thermoelectric water use and sectoral consumptive use until 1960. According to the USGS estimates, national total water withdrawals have increased from 1022.1 billion dm^3 per day in 1960 to 1521.7 billion dm^3 per day in 1995. Throughout the period, thermoelectric generation has remained the sector with the largest amount of water withdrawals, whose proportion increases from 37.5% in 1960 to 47.2% in 1995 (Figure 1). Similar to the trend of water withdrawals, national water consumptive use has increased from 230.9 billion dm^3 per day in 1960 to 378.5 billion dm^3 per day in 1995. Agriculture by far consumes the largest amount of water, accounting for about 80% of national total consumption. Water consumption by thermoelectric generation, however, has undergone a rapid increase. Its proportion increased from 0.8% in 1960 to 13.9% in 1995 (Figure 2).

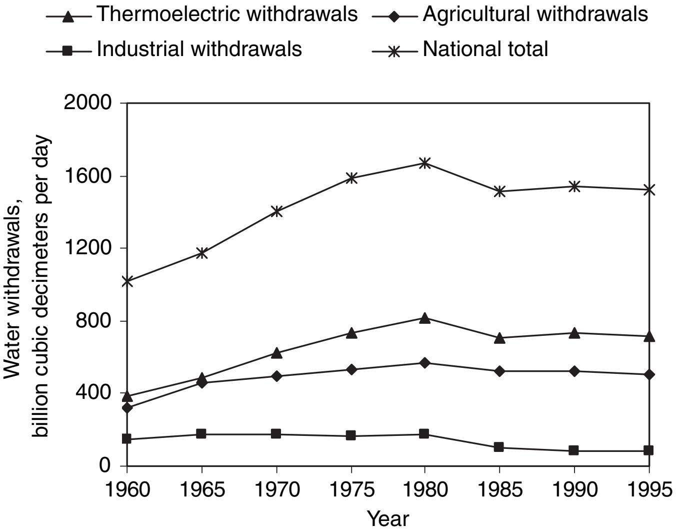

FIGURE 1. Historical Water Withdrawals in Thermoelectric Generation, Agriculture, and Industrial Manufacturing, 1960-95.

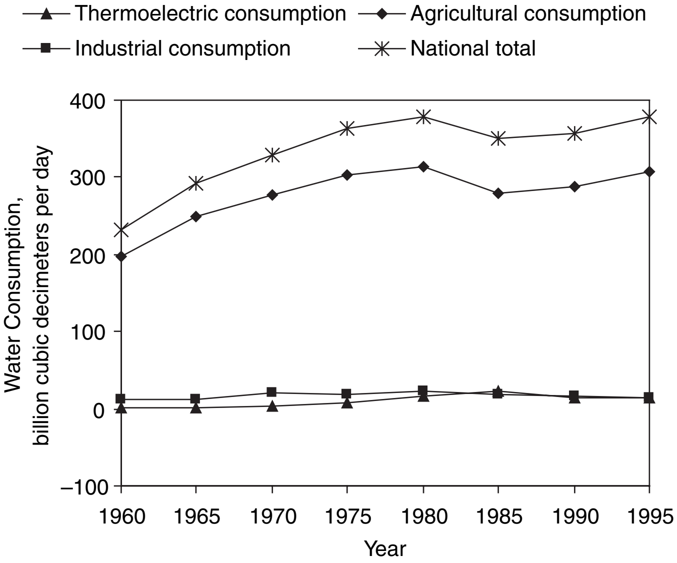

FIGURE 2. Historical Consumptive Water Use in Thermoelectric Generation, Agriculture, and Industrial Manufacturing, 1960-95.

Most of the water used in thermoelectric power generation is for cooling purposes. In general, there are three types of cooling systems: wet once-through cooling systems, wet closed-cycle cooling systems, and dry cooling systems. In the once-through systems, water is withdrawn from a natural water body (such as a river, lake, estuary, or ocean) and it flows through a heat exchanger to cool the steam, and is subsequently returned to the source (Huston, 1975). In the wet closed-cycle cooling systems, the heated water from the condenser is pumped up to the top of a tower and then falls down. By forcing the cool air to pass through the falling water, some heat is exchanged and some water evaporates. This type of cooling system can reduce the total volume of water withdrawals by nearly 95% compared to the volume required for once-through cooling (Harte and El-Gasseir, 1978). However, this type of cooling system also needs much larger amount of water consumption. Recently, some electric utilities have begun to use dry cooling towers or hybrids (Bartz, 1994). In the dry cooling systems, the condenser coolant is enclosed within a piping network with no direct air/water interface. The heat is dissipated to the atmosphere through conduction and radiation rather than evaporation. Thus, dry cooling systems use little water for cooling. Currently, dry cooling systems cost three to five times as much as wet cooling towers, and the high expenses limit the wide adoption of this technology. Thus, this type of cooling system in not examined in the study.

Theoretical water requirements for once-through cooling systems are a function of the amount of "waste" heat that has to be removed in the process of condensing steam. Large amount of water is needed because the heat is removed by conduction which is less efficient than heat removal by radiation or convection. The amount of water for one megawatt (MW) of electric generation capacity can be calculated as (Backus and Brown, 1975):

$$L = \frac{6823(1-e)}{Te} \tag{1}$$

where L is the amount of water in gallons per minute per MW of generating capacity; T the temperature rise of the cooling water in °F; and e is the thermodynamic efficiency of the power plant, expressed as decimal fraction.For example, in a coal-fired plant with thermal efficiency of 40% and the condenser temperature rise of 20°F, the water flow rate would be 512 gallons per minute (gpm) per MW. For a typical 650 MW plant, the flow rate would be 332,600 gpm or nearly 480 million gallons per day (or approximately 31 gallons/kWh (or 120 dm^3/kWh) at 100% of generation capacity).

In recirculating systems with cooling towers, theoretical make-up water requirements can be calculated as (Croley *et al.*, 1975):

$$W = E \cdot \frac{1}{1 - \frac{C}{C_o}} \tag{2}$$

where E is the evaporative water loss which for a typical mean water temperature of 80°F can be calculated as:

$$E = (1.91145 \cdot 10^{-6}) \cdot aQ \tag{3}$$

where a is the fraction of heat dissipated as latent heat of evaporation (for evaporative towers a = 75% to 85%); and Q the rate of heat rejection by the plant in Btu/h, which can be calculated as:

$$Q = 3414426 \cdot P \cdot \frac{1-e}{e} \tag{4}$$

where P is the rated capacity of the plant in MW; and e the efficiency of plant expressed as a fraction.

Again for a typical 650 MW coal-fired plant with 40% efficiency the heat rejection would be 3,329 million Btu/h and the evaporative water loss would be 5,090 gpm. At the recycling ratio c/c_o of ¼, the make-up water flow (W) would be 6,788 gpm or 0.63 gallons/kWh (2.4 dm^3/kWh).

The actual rates of water use are likely to be different from the theoretical values for a number of reasons. Undoubtedly, the type of the cooling system installed is the most significant determinant of water use for thermoelectric power generation. Large differences in unit water use per kilowatt-hour of electricity generation among different types of cooling systems were reported in previous studies (Harte and El-Gasseir, 1978; Gleick, 1993; Baum *et al.*, 2003). However, cooling system type is not the sole determinant of thermoelectric water use. Previous studies indicate that the type of generation, fuel type, water sources and cost also contribute to the variability of water use (Cootner and Lof, 1965; Wollman and Bonem, 1971; Young and Thompson, 1973; Brown, 2000). Unfortunately, no substantial studies of determinants of unit thermoelectric water use have been conducted.

The purpose of this paper is to examine the variance in unit thermoelectric water use per kilowatt-hour of electric generation at the plant and cooling system level and to evaluate the determinants of water use. This paper is part of on-going research project at Southern Illinois University – Carbondale and is based on two earlier studies: an analysis of water use trends in the United States (Dziegielewski *et al.*, 2002) and a doctoral dissertation on thermoelectric water use (Yang, 2004).

Data and Methods

The Energy Information Administration (EIA) at the U.S. Department of Energy (DOE) collects and publishes data on electricity generation in the United States. EIA uses a series of survey forms to collect information on various aspects of electricity generation in the country. One of these forms, "Steam-Electric Plant Operation and Design Report (form EIA-767)," is designed to collect information on organic- or nuclear-fueled steam thermoelectric power plants with a generator nameplate rating of 10 or more megawatts. The information collected is then compiled into the EIA 767 databases that, among other information, contain records of water use, boiler and cooling system configuration, and electricity generation data for the surveyed thermoelectric power plants. In this study, the EIA 767 databases for the calendar years from 1996 to 2000 were downloaded from the EIA website (http://www.eia.doe.gov/cneaf/electricity/page/eia767hist.html).

The original data contained in EIA-767 databases are reported at different levels of individual observations. For example, electricity generation data are recorded at the generator level; fuel source data are recorded at the boiler level; while water use data are recorded at the cooling system level. However, in typical thermoelectric power plants, boilers, generators, and cooling systems are interconnected. For example, one cooling system can be connected to several generators or boilers. One boiler or generator can also be served by several cooling systems. This multi-level data reporting makes it difficult to associate the reported thermoelectric water use with corresponding thermoelectric generation, fuel type, cooling system type, and other influencing factors. Therefore, these multi-level data had to be aligned to the same level before they could be used for water use analysis. The procedure for aligning the data consisted of two steps. First, the interconnected cooling systems, boilers, and generators were identified and grouped into a new single generation unit represented by a unique system identification number (ID). Second, the values of the following seven factors were determined for each newly created unit: (1) total annual water use; (2) cooling system type and age; (3) average cooling water temperature rise in once-through cooling systems; (4) type of the fuels burned by the corresponding generators; (5) type of the water sources for thermoelectric cooling; (6) total annual net electricity generation and generation capacity by the corresponding generators; and (7) operational efficiency and thermal efficiency.

The EIA767 database records seven types of cooling systems. These include: once-through systems with cooling ponds or canals, fresh water once-through systems, saline once-through systems, recirculating systems with cooling ponds or canals, recirculating systems with forced draft cooling towers, recirculating systems with induced draft cooling towers, and recirculating systems with natural draft cooling towers. If the cooling systems included in the new unit are of the same type, the cooling system type of the new unit was coded with the same value. Otherwise, the newly created unit's cooling system type assumed one of the following three values: mixed once-through cooling systems (the new unit only includes once-through cooling systems), mixed recirculating cooling systems (the new unit only includes recirculating systems), and mixed once-through and recirculating cooling systems (the new unit includes both once-through and recirculating systems).

In the EIA767 database, there are five major types of water sources for thermoelectric cooling purpose, and they include fresh ground water sources, surface fresh water sources, surface saline water sources, public delivery, and sewage. If the cooling systems in the new unit used a single water source, the water source type of the new unit was coded with that value. Otherwise, the new unit's water source was coded as mixed water sources.

Four major types of fuels are used in steam electric power generation: coal, petroleum, natural gas, and nuclear fuels. EIA767 reports the fuel type for each boiler up to three levels of predominance. Only the fuel type of the first predominance was considered in this study. If all of the boilers that were included in the new unit burned the same type of fuel, the fuel type of the new unit was coded with that value. Otherwise, the new unit's fuel type was coded as mixed fuels.

Thermoelectric water use was estimated by simply summing the amount of water use by all of the included cooling systems within the generation unit. Likewise, electricity generation and generation capacity were estimated by summing those of each included generator. Using Equation (5), data on electricity generation and generation capacity were used to estimate operational efficiency of the generation unit. Operation efficiency is one commonly used power plant performance factor and it is defined as the ratio between the total electricity produced and the total potential electricity that could have been produced if the plant operated at 100%.

$$\mu_{\mathrm{oe}} = 100E/(C * 24 * 365) \tag{5}$$

where μ_{oe} is the operational efficiency (%); E the annual electricity generation (kWh); and C is the generation capacity (kW).

To estimate thermal efficiency, another commonly used power plant performance factor, total supplied heat was estimated by summing the heat content of all of the fuels burned in the included boilers. Using Equation (6), data on electricity generation and supplied heat were used to estimate the thermal efficiency of the generation unit. However, the EIA 767 databases did not report heat data for nuclear power plants. Thus, it was impossible to use the Equation (6) to calculate thermal efficiency for the nuclear generation units. Based on several reports, the thermal efficiency of all nuclear generation units was assumed to be 34% (Makhijani, 1998; Nuclear Management Company, 2002; Nuclear Energy Institute, 2005).

$$\mu_{\mathrm{te}} = 360000E/H \tag{6}$$

where μ_{te} is the thermal efficiency (%); E the annual electricity generation (kWh); and H the annual supplied heat (kJ).

Finally, cooling system age was calculated as the average age of the cooling systems included within the generation unit. EIA 767 form reports water temperature at both the intake and discharge outlet for once-through cooling systems in winter and summer peak load months. The average temperature rise in once-through cooling systems was calculated as the average temperature difference between discharge and outlet of the two seasons.

A standardized measure of water intake volume in thermoelectric generation is the amount of water use for generating one kilowatt-hour (1 kWh) of electrical energy, referred to here as unit or unitary thermoelectric water use. Thermoelectric water use and generation data of the new generation units created in the data alignment procedures were used to calculate the actual quantities of water use for generating one kWh of energy. The distribution of unit thermoelectric water use by different types of cooling systems were estimated and examined.

Multiple regression procedures were used to identify the major determinants of thermoelectric water use (both withdrawals and consumptive use) and estimate their respective impacts. Four categories of potential determinants were examined (Table 1). These include: (1) specific types of cooling systems; (2) fuel types; (3) operation conditions; and (4) water sources. The variables created for the regression procedure are binary indicator variables except those on operational conditions.

RESULTS AND DISCUSSION

Thermoelectric Water Withdrawals

Average Rates of Unit Thermoelectric Withdrawals. Table 2 compares the unit thermoelectric withdrawals for 10 different configurations of cooling systems. The mean values of unit withdrawals indicate that the 10 types of systems can be separated into three groups: (1) cooling systems that are at least partially composed of once-through cooling, (2) recirculating cooling systems with cooling ponds or canals, and (3) recirculating cooling systems that are at least partially composed of cooling towers. As expected, the mean values of unit withdrawals by once-through cooling systems are much larger than those of recirculating systems. The average amount of unit thermoelectric withdrawals by all of the once-through cooling systems are above 150 dm^3/kWh, while recirculating systems with cooling ponds or canals average around 100 dm^3/kWh and all the recirculating systems with cooling towers average below 5 dm^3/kWh.

TABLE 1. Potential Determinants of Thermoelectric Withdrawals.

Categories	Potential Determinants (and Indicator Variables) of Water Withdrawals
Cooling system types	Once through with cooling ponds or canals
	Fresh water once-through systems
	Saline once-through systems
	Mixed once-through cooling systems
	Recirculating cooling systems with cooling ponds or canals
	Forced draft cooling towers
	Induced draft cooling towers
	Natural draft cooling towers
	Mixed recirculating cooling systems
	Mixed once-through and recirculating cooling systems
Fuel types	Coal as fuel
	Natural gas as fuel
	Nuclear fuels
	Petroleum as fuel
	Mixed fuels
Operation conditions	Operational efficiency
	Thermal efficiency
	Age of cooling system
	Average cooling water temperature rise
	Average summer temperature (May to September)
	Average annual temperature
Water sources	Fresh ground water
	Publicly delivered water
	Sewage
	Surface fresh water
	Surface saline water
	Mixed water sources

Despite the large difference in the mean values of unit thermoelectric withdrawals between the three groups of cooling systems, the actual distribution of unit withdrawals among individual plants shows considerable overlap across different types of cooling systems (Table 2). The actual amount of unit withdrawals by each type of cooling system also shows large variability. The coefficients of variation of unit withdrawals by recirculating cooling systems

TABLE 2. Comparison of Unit Thermoelectric Withdrawals Under Different Types of Cooling System Configurations (dm^3/kWh).

Cooling Systems	**Mean**	***N***	**Median**	**Standard Deviation**	**Coefficient of Variation (%)**	**Min.**	**Max.**
Once through with cooling ponds or canals	178.67	175	155.20	90.1	50.4	4.16	526.6
Once through, fresh water	191.16	1296	171.86	94.6	49.5	0.04	563.7
Once through, saline water	232.05	444	210.85	98.0	42.3	3.03	561.0
Mixed once through cooling	213.12	53	196.08	136.3	63.9	0.38	561.0
Mixed once through and recirculating cooling	158.99	164	122.65	125.7	79.0	2.65	536.8
Recirculating with cooling ponds or canals	103.72	249	64.35	122.3	117.9	0.38	536.8
Recirculating with forced draft cooling towers	4.54	490	2.65	6.1	133.3	0.08	52.2
Recirculating with induced draft cooling towers	4.92	322	2.27	9.1	184.6	0.19	65.1
Recirculating with natural draft cooling towers	4.54	258	3.41	4.9	108.3	0.76	40.5
Mixed recirculating	3.03	56	2.65	1.9	62.5	0.38	7.6

are above 100% while they are all less than 80% for the once-through cooling systems. The observed large variability in the unit thermoelectric withdrawals within each cooling system type implies that there must be other factors other than the amount of heat being removed that influence the amount of water withdrawals needed for thermoelectric power generation. Multiple regression models were used to identify these factors and evaluate their influence on the unit thermoelectric water withdrawals.

Determinants of Unit Thermoelectric Withdrawals. To understand the variability in unit withdrawals, regression models were developed for each of the three major categories of cooling systems: once-through cooling systems, recirculating cooling systems with cooling ponds or canals, and recirculating cooling systems with cooling towers. Table 3 shows the linear regression models for unit withdrawals in each of the three types of cooling systems, which were estimated using the stepwise regression procedure of the JMP 4.0 software. The columns of partial R^2 describe the incremental contribution of each independent variable to the explained variance. The last row of the table summarizes the main statistics for the estimated model.

The modeling results for once-through cooling systems show that besides cooling system types, the operational conditions, water sources, and fuel types are among the important determinants of thermoelectric withdrawals. Operational efficiency is the first variable selected in the model with a partial R^2 of 0.21. The rationale for its negative coefficient is that the cooling systems may not be adjusting the pumping of cooling water to match the actual amount of electricity generation and therefore the actual amount of heat that must be dissipated. Thus, when other factors are the same, the higher the rate of

TABLE 3. Regression Model of Unit Thermoelectric Withdrawals.

Once-Through Cooling Systems			**Recirculating Systems With Cooling Ponds or Canals**			**Recirculating Cooling Systems Other Than With Cooling Ponds or Canals**		
Explanatory Variables	**Coeff.**	**Partial R^2**	**Explanatory Variables**	**Coeff.**	**Partial R^2**	**Explanatory Variables**	**Coeff.**	**Partial R^2**
Intercept	448.81^{*}	–	Intercept	$288.00^{\dagger}$	–	Intercept	23.46^{*}	–
Operational efficiency	-1.72^{*}	0.208	Coal as fuel	-73.98^{*}	0.152	Operational efficiency	-0.11^{*}	0.102
Average cooling water temperature rise	-3.22^{*}	0.099	Thermal efficiency	-13.89^{*}	0.070	Age of cooling system	$0.04^{\dagger}$	0.030
Thermal efficiency	-4.16^{*}	0.022	Mixed water sources	-236.04^{*}	0.063	Recirculating with natural draft cooling towers	1.06^{*}	0.029
Nuclear fuels	53.29^{*}	0.013	Average summer temperature	4.87^{*}	0.056	Coal as fuel	-3.36^{*}	0.036
Age of cooling system	1.12^{*}	0.008	Public water delivery	-120.65^{*}	0.027	Natural gas as fuel	-6.88^{*}	0.029
Surface saline water sources	16.97^{*}	0.008	Operational efficiency	$-0.85^{\dagger}$	0.012	Fresh ground water sources	-1.41^{*}	0.011
Mixed fuels	-36.93^{*}	0.004				Public water delivery	-3.01^{*}	0.006
Petroleum as fuel	$17.17^{\dagger}$	0.002				Average summer temperature	0.06^{*}	0.004
						Thermal efficiency	-0.41^{*}	0.004
Mean Y = 197.0 dm^3/kWh, N = 1845, R^2 = 0.36, Root MSE = 72.1 dm^3/kWh			Mean Y = 104.1 dm^3/kWh, N = 235, R^2 = 0.38, Root MSE = 98.9 dm^3/kWh			Mean Y = 4.3 dm^3/kWh, N = 1113, R^2 = 0.25, Root MSE = 4.7 dm^3/kWh		

* Means $p < 0.01$; † means $p < 0.05$. Coeff., coefficient.

utilization of generation capacity, the smaller is the unit volume of water withdrawals. Average rise in cooling water temperature is the second variable selected in the model and it also has a negative coefficient. Higher temperature rise in cooling water indicates that more heat is being removed with the same amount of water. Thus, less cooling water is needed for the same amount of thermoelectricity generation. The next variable selected in the model is thermal efficiency with negative coefficient. Higher thermal efficiency indicates that larger proportion of source energy has been converted into electricity. Thus, there is less amount of residual heat to be cooled down from the process, which leads to less cooling water demand. In addition, the modeling results indicate that when other factors are the same, on average, once-through systems tend to have larger amounts of unit water withdrawals if they have operated for a long period of time (system age), use nuclear fission, mixed fuels, or petroleum as fuel sources, or use surface saline water as the source of cooling water.

In the regression model of unit withdrawals in recirculating systems with cooling ponds or canals, average summer air temperature is the only variable selected in the model with a positive coefficient. The increase in air temperature can induce an increase in water body temperature, thus causing a smaller temperature difference between cooling water and steam. As a result, more water would be needed to cool down the same amount of steam. The negative coefficients of the remaining variables in the model indicate that, on average, power plants with recirculating cooling ponds or canals that have higher thermal or operation efficiency, burn coal, or obtain cooling water from public supply or use mixed water sources are likely to withdraw less water per 1 kWh of electricity generation. One reason why water source variables have significant impacts on unit withdrawals is because, to some extent, water sources reflect the cost of water for power generation and water obtained from more expensive sources is more likely to be conserved. For example, water from public supply is generally more expensive than water obtained from other sources. The higher water cost may also motivate the operators of power plants to conserve water, resulting in a relatively small amount of unit water withdrawals.

In the regression model of unit withdrawals in recirculating systems with cooling towers, a smaller percentage of variance was explained than in the other two models. However, the total variance in this group is much smaller than in the other groups. Like in the previous two models, operation efficiency and thermal efficiency were both included in the model with negative coefficients. Two fuel source indicators were included in the model with negative coefficients indicating that on the average the power plants with recirculating cooling towers that rely on coal or natural gas as the energy inputs have less unit thermoelectric withdrawals than plants with other fuels when other factors are the same. Likewise, the negative coefficients of two water source indicators indicate the power plants getting water from public supply or fresh ground water sources have less unit thermoelectric withdrawals than plants using other sources. Finally, consistent with the other two models, average summer temperature and cooling system age are included with positive coefficients.

The historical data on water withdrawals in the United States indicate that over the past five decades, thermoelectric power generation has become increasingly water-use efficient, as shown by the decrease in the average amount of water withdrawal for generating 1 kWh of electricity (Dziegielewski *et al.*, 2002). One major factor leading to the decreasing amount of water withdrawals is the increasing proportion of closed-loop (i.e., recirculating) cooling systems for thermoelectric cooling purpose (Yang, 2004). A multiple regression model was used to estimate the average difference in unit thermoelectric withdrawals between the once-through and recirculating cooling systems (Table 4). In this model, binary indicator variables were used to designate different types of cooling systems. Like in the previous three models, some operational condition variables such as cooling system age, fuel source indicators, and water source indicators were included in the model through a stepwise procedure. The coefficients of these

TABLE 4. Linear Model of Unit Thermoelectric Withdrawals in All Cooling Systems.

Explanatory Variables	**Coeff.**	**Partial R^2**
Intercept	296.67*	–
Age of cooling system	0.87*	0.246
Recirculating with forced draft cooling towers	−162.30*	0.082
Recirculating with induced draft cooling towers	−157.74*	0.098
Recirculating with natural draft cooling towers	−150.03*	0.083
Operational efficiency	−1.16*	0.043
Recirculating with cooling ponds or canals	−91.68*	0.033
Mixed recirculating cooling systems	−156.59*	0.031
Surface saline water sources	25.24*	0.010
Thermal efficiency	−3.44*	0.005
Petroleum as fuel	33.85*	0.003
Mixed once through and recirculating cooling systems	−27.67*	0.002
Nuclear fuels	20.01*	0.002
Fresh ground water sources	−23.32*	0.001
Average summer temperature	0.56*	0.001
Public water delivery	−18.14†	0.001
Mean $Y = 125.4$ dm^3/kWh, $N = 3443$, $R^2 = 0.64$, Root MSE = 70.8 dm^3/kWh		

*Means $p < 0.01$; †means $p < 0.05$. Coeff., coefficient.

variables also show consistent signs. All of the recirculating cooling system indicators were also selected and have negative coefficients. The coefficients for the indicators of mixed recirculating cooling systems and recirculating cooling systems with forced draft cooling towers, induced draft cooling towers, and natural draft cooling towers were all below -150 dm^3/kWh. This indicates that on average, a replacement of once-through cooling systems with recirculating (closed-loop) cooling systems with cooling towers could save more than 150 dm^3 of water withdrawals per 1 kWh of electricity generation. The indicator of recirculating cooling system with cooling ponds or canals had a negative coefficient of −91.7 dm^3/kWh. This indicates that on average recirculating systems with cooling ponds or canals could save about 91.7 dm^3 decimeters of water withdrawals per 1 kWh of electricity if they replaced the once-through cooling systems. Finally, the indicator for mixed once-through and recirculating cooling systems had a negative coefficient of −27.7 dm^3/kWh. This indicates that these cooling systems could on the average save about 27.7 dm^3 of water withdrawals to generate 1 kWh of electricity as compared with once-through systems.

Thermoelectric Water Consumption

Average Rates of Unit Thermoelectric Water Consumption. While the replacement of once-through cooling systems with recirculating cooling towers would clearly result in substantial reduction of water withdrawals, it would cause considerably more water consumption. Unlike water withdrawals, water consumed represents the amount of water that will not be available for other local uses. Thus, consumptive use is an important component of thermoelectric water use.

However, our analysis of consumptive thermoelectric use has been hampered by the inferior quality of the EIA-767 data on consumptive losses of water. Understandably, data on consumptive water use are much more difficult to collect than those on thermoelectric withdrawals, resulting in many observations being rough estimates. After excluding the observations with either missing values or unusually high unit consumptive water use (>15 dm^3/kWh), the consumptive water use models still yield considerable poorer explanatory power than the water withdrawal models. Thus, caution needs to be exercised when interpreting the results of the following analysis of consumptive water use.

Table 5 compares the unit thermoelectric consumptive use for the 10 different configurations of cooling systems. Like the case of water withdrawals, there exists considerable variability in the amount of unit consumptive water use within and among different types of cooling systems. As one would expect, the mean values of unit consumptive use by recirculating cooling towers are much larger than those of once-through cooling systems. Nevertheless, the mean values of unit consumptive use by once-through cooling systems are still probably "inflated" by a few observations with unusually large values. Consequently, the median value is a better indicator for comparing consumptive use by different cooling systems. As shown in Table 5, median unit consumptive use all falls between 2 and 3 dm^3/kWh in recirculating cooling towers and is shown as zero in once-through cooling systems.

Determinants of Unit Thermoelectric Water Consumption. Like water withdrawals, consumptive water use exhibits large variability. Regression models were developed to evaluate the impacts of potential factors on unit consumptive use. However, because of the large amount of records with zero consumptive water use in the data for once-through cooling systems, only a model for all systems combined is developed in this section that covers all cooling systems with consumptive use data (Table 6).

TABLE 5. Comparison of Unit Thermoelectric Consumptive Use Under Different Types of Cooling System Configurations (dm^3/kWh).

Cooling Systems	Mean	*N*	Median	Standard Deviation	Coefficient of Variation (%)	Min.	Max.
Once through with cooling ponds or canals	0.86	176	0.00	1.34	156.3	0.00	6.72
Once through, fresh water	0.32	1328	0.00	0.91	284.5	0.00	7.08
Once through, saline water	0.06	477	0.00	0.47	846.6	0.00	5.94
Mixed once through cooling	0.28	55	0.00	0.70	247.7	0.00	2.77
Mixed once through and recirculating cooling	0.95	166	0.33	1.30	136.5	0.00	6.35
Recirculating with cooling ponds or canals	0.83	202	0.00	1.33	161.4	0.00	6.96
Recirculating with forced draft cooling towers	2.43	472	2.06	1.37	56.2	0.03	7.42
Recirculating with induced draft cooling towers	2.34	296	2.15	1.09	46.6	0.39	7.45
Recirculating with natural draft cooling towers	2.58	250	2.27	1.33	51.4	0.45	7.02
Mixed recirculating	2.15	50	2.48	1.03	48.0	0.19	4.97

TABLE 6. Linear Model of Unit Thermoelectric Consumptive Use in All Cooling Systems.

Explanatory Variables	**Coeff.**	**Partial R^2**
Intercept	3.78*	–
Recirculating with natural draft cooling towers	1.09*	0.015
Recirculating with forced draft cooling towers	0.96*	0.024
Recirculating with induced draft cooling towers	1.04*	0.022
Operational efficiency	−0.02*	0.021
Nuclear as fuel	0.62*	0.014
Natural gas as fuel	−0.42*	0.010
Fresh ground water sources	−0.44*	0.005
Public water delivery	−0.53*	0.004
Mixed recirculating cooling systems	0.61*	0.005
Recirculating with cooling ponds or canals	0.41*	0.004
Thermal efficiency	−0.03†	0.003
Mean Y = 2.2 dm^3/kWh, N = 1605, R^2 = 0.13, Root MSE = 1.3 dm^3/kWh		

*Means $p < 0.01$; †means $p < 0.05$. Coeff., coefficient.

Overall, the model can explain 13% of the variability in unit consumptive use. Similar to water withdrawal models, some operational conditions, fuel source indicators, and water source indicators are included in the models with consistent signs of coefficients. What is different is that in the consumptive use model, recirculating cooling systems indicators are all selected with positive coefficients indicating more water consumption. The coefficients for three types of recirculating cooling systems using cooling towers, for example, are all around 1.0 dm^3/kWh. This indicates that on average, the cooling towers consume 1.0 dm^3 more water then the once-through cooling systems for generating 1 kWh of electricity.

CONCLUSIONS

Thermoelectric power plants' massive water demand could have significant impacts on local water resources. There have been reports of adverse environmental impacts of thermoelectric power plants because of the required large amount of water withdrawals or consumption. Nevertheless, much fewer water use studies have been conducted for thermoelectric generation compared with other water using sectors. One possible reason for this is that thermoelectric water use is assumed to be strictly determined by physical laws. Through the analysis of water use data of existing steam thermoelectric power plants, this study shows that this is not the case. Both the amount of thermoelectric water withdrawal and consumption per kilowatt-hour of thermoelectric generation varies among different plants. Besides cooling system type, both thermoelectric water withdrawal and consumption are also influenced by factors like water source, fuel type and operational conditions. For example, when other factors are the same, unit thermoelectric water withdrawal and consumption tend to be lower when power plants rely on public supply, but higher when the power plants use nuclear fission as the energy source. In addition, power plants also tend to have lower unit water use when they are run with higher operational and thermal efficiencies.

However, even after variables that designate cooling systems, fuel types, water sources, and operation conditions are all considered, there is still much variance to be explained in the amount of unit thermoelectric water withdrawal and consumption. This indicates that there are differences in the amounts of unit thermoelectric water withdrawal and consumption that may be attributed to some inefficiency in water use. An important conclusion of this study is that there may be considerable potential for water conservation to further reduce the amount of thermoelectric water withdrawal and consumption per kilowatt-hour of thermoelectric generation in existing thermoelectric power plants. The water use models presented here can be used to estimate the "norm" or "standard value" for unit thermoelectric water use for each type of power plant, thus providing some pragmatic basis for undertaking improvements in the efficiency of water use in power plants and cooling systems that exceed the standard values. An ongoing research project under the USGS Grant No. 2004IL56G is aimed at developing some useful benchmarks of water usage at different types of thermoelectric power plants.

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LITERATURE CITED

Backus, C.E. and M.L. Brown, 1975. *Water Requirements for Solar Energy*. In: Water Management for the Electric Power Industry, E.F. Gloyna, H.H. Woodson, and H.R. Drew, Water Resources Symposium #8, Center for Research in Water Resources, The University of Texas at Austin, pp. 270-279.

Bartz, J.A, 1994. New Development in Cooling Towers. *Power Engineering* 98(6):23-25.

Baum, E., J. Chaisson, B. Miller, J. Nielsen, M. Decker, D. Berry, and C. Putnam, 2003. *The Last Straw: Water Use by Power Plants in the Arid West*. Hewlett Foundation Energy Series.

http://www.catf.us/publications/reports/The_Last_Straw.pdf, accessed September 17, 2005.

Brown, T.C, 2000. Projecting U.S. Freshwater Withdrawals. *Journal of Water Resources Research* 36(3):769-780.

Canadian Broadcast Corporation, 2002. *Environmentalists Score Victory in Sumas 2 Fight*. http://www.cbc.ca/canada/british-columbia/story/2002/12/09/bc_sumas20021209.html, accessed September 17, 2005.

Cootner, P.H. and G.O.G. Lof, 1965. Water Demand for Steam Electric Generation. *An Economic Projection Model*. Johns Hopkins Press. Baltimore, Maryland.

Croley, T.E. II, V.C. Patel, and M.S. Cheng, 1975. *The Water and Total Optimization of Wet and Dry-wet Cooling Towers for Electric Power Plants*. Iowa Institute of Hydraulic Research Report No. 163. The University of Iowa, Iowa City, Iowa, January 1975.

Dziegielewski, B., S.C. Sharma, T. Bik, H. Margona, and X. Yang, 2002. *Analysis of Water Use Trends in the United States*: 1950-1995. Southern Illinois University, Carbondale, Illinois, Report on Grant No. 99HQGR0222, USGS National Competitive Grants Program, United States Geological Survey, Reston, Virginia.

Frederick, K.D, 1995. America's Water Supply: Status and Prospects for the Future. http://www.gcrio.org/CONSEQUENCES/spring95/Water.html, *accessed* March 15, 2005.

General Accounting Office, 2003. Freshwater Supply: States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages. Report to Congressional Requesters GAO-03-514. Washington, District of Columbia.

Gleick, P.H, 1993. Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford University Press. New York.

Gleick, P.H, 1994. *Water and Energy*. Annual Review of Energy and Environment. 19: 267-299.

Harte, J. and M. El-Gasseir, 1978. Energy and Water. *Science*, 199(4329):623-634.

Horvath, R.S. and M.M. Brent, 1972. Thermal Pollution and the Aquatic Microbial Community: Possible Consequences. *Environmental Pollution* 3(2):143-146.

Huisman, J., H.J.G. Ten Hoopen, and A. Fuchs, 1980. The Effect of Temperature Upon the Toxicity of Mercuric Chloride to *Scenedesmus acutus*. *Environmental Pollution Series A, Ecological and Biological* 22(2):133-148.

Huston, R.J., 1975. An Overview of Water Requirements for Electric Power Generation. In: *Water Management for the Electric Power Industry*, E.F. Gloyna, H.H. Woodson, and H.R. Drew, Water Resources Symposium #8, Center for Research in Water Resources, The University of Texas at Austin, pp. 39-49.

Johnson, C, 2001a. Proposed Diversion Dam Rejected. Billings Gazette. June 28.

Johnson, C, 2001b. Drought Takes Its Toll in Urban Area. Billings Gazette. November 16.

MacKichan, K.A, 1951. Estimated Water Use in the United States in 1950. U.S. Geological Survey Circular 115.

MacKichan, K.A, 1957. Estimated Water Use in the United States in 1955. U.S. Geological Survey Circular 398.

MacKichan, K.A. and J.C. Kammerer, 1961. Estimated Water Use in the United States in 1960. U.S. Geological Survey Circular 456.

Makhijani, A, 1998. *Nuclear Power: No Solution to Global Climate Change*. Science for Democratic Action. 6 (3). 00-00. http://www.ieer.org/ensec/no-5/nuclr-no.html, *accessed* September 17, 2005.

Morlock, B, 2002. ACC Nixes Generation Station near Eloy. Tucson Citizen. January 31.

Mostertman, L.J, 1976. Water Quality: An Overview. *Agro-Ecosystems* 3:239-251.

Murray, C.R, 1968. Estimated Water Use in the United States in 1965. U.S. Geological Survey Circular 556.

Murray, C.R. and E.B. Reeves, 1972. Estimated Water Use in the United States in 1970. U.S. Geological Survey Circular 676.

Murray, C.R. and E.B. Reeves, 1977. Estimated Water Use in the United States in 1975. U.S. Geological Survey Circular 765.

Nuclear Energy Institute, 2005. *Comparative Measures of Power Plant Efficiency*. http://www.nei.org/index.asp?catnum=2&catid=262, *accessed* September 17, 2005.

Nuclear Management Company, 2002. *U.S. Nuclear Power Plant Performance*. http://www.nmcco.com/education/facts/business/perform.htm, *accessed* September 17, 2005.

Seattle Post – Intelligencer, 2002. *Power Plant Shelved After Water Use Denied*. August 2.

Solley, W.B., E.B. Chase and W.B. Mann IV, 1983. Estimated Water Use in the United States in 1980. U.S. Geological Survey Circular 1001.

Solley, W.B., C.F. Merk, and R.R. Pierce, 1988. Estimated Water Use in the United States in 1985. U.S. Geological Survey Circular 1004.

Solley, W.B., R.R. Pierce, and H.A. Perlman, 1993. Estimated Water Use in the United States in 1990. U.S. Geological Survey Circular 1081.

Solley, W.B., R.R. Pierce, and H.A. Perlman, 1998. Estimated Water Use in the United States in 1995. U.S. Geological Survey Circular 1200.

Wollman, N. and G.W. Bonem, 1971. The Outlook for Water: *Quality, Quantity, and National Growth*. Johns Hopkins Press, Baltimore, Maryland.

Yang, X, 2004. Analysis of Thermoelectric Water Use in the United States. PhD. Dissertation. Southern Illinois University, Carbondale, Illinois.

Young, H.P. and R.G. Thompson, 1973. Forecasting Water Use for Electric Power Generation. *Water Resources Research* 9(4): 800-807.

Youngbluth, M.J, 1976. Zooplankton Populations in a Polluted, Tropical Embayment. *Estuarine and Coastal Marine Science.* 4(5):481-496.