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RESOURCE ANALYSIS: WATER AND ENERGY AS LINKED RESOURCES

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ABSTRACT

RESOURCE ANALYSIS: WATER AND ENERGY AS LINKED RESOURCES

Energy and water are linked resources. This pilot study examines the relationship between energy and water from a direction opposite to that of most studies. We are concerned here with evaluating the energy required to supply and treat water, rather than with the water requirements of energy production. The primary energy requirements for three sectors of water management--municipal water supply, municipal sewage treatment, and water for irrigation--are evaluated. Six major cities, Chicago, Denver, Los Angeles, New Orleans, San Antonio, and St. Louis, are used as indicators of the national trend in energy requirements to supply water to municipalities. Nationwide data provided by the federal Environmental Protection Agency for 1977 and 1990 are used to determine the rate of change of energy required to treat municipal sewage over this period. The energy required to supply water for irrigation is estimated for three regions in the Southwest: Kern County, California; the Texas high plains; and San Carlos, Arizona.

Historic trends and prospects for future development are used to estimate future energy requirements for each of these water sectors. The projections are compared to expected increases in national energy consumption. The results indicate that:

1. Regional differences in the amount of energy needed to supply water are very large, increasing in some places and decreasing in others.
2. Significant nationwide increases are likely for the energy required to treat sewage.
3. Noncritical short-term increases will occur in the total energy requirement to supply irrigation water, but after the year 2000, the Southwest faces an extremely difficult choice in balancing its resources of energy, water, and agricultural land, particularly in light of its growing urban demands.

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PREFACE

This report is presented as a pilot study designed to determine how critical the change will be in the demand for energy to supply and treat water between now and the end of the century. To estimate the magnitude of this demand, we examined the primary energy requirements of three sectors of water supply and treatment: municipal water supply, municipal sewage treatment, and agricultural irrigation. In each area, we asked both how much of the United States energy demand goes to each water use and whether or not the growth rate in the amount of energy required to process water for these different uses will exceed the projected rate of increase in energy consumption for the nation as a whole. Estimates of the energy consumption over time in the United States are taken from the Federal Energy Administration's *Water Requirements, Availabilities, Constraints, and Recommended Federal Actions, Project Independence* of November 1974.

The energy requirements of supplying water are considered for six major cities: Chicago, Denver, Los Angeles, New Orleans, San Antonio, and St. Louis. The energy requirements of these urban areas were analyzed to provide an indication of the extent of future increases in the amount of energy required to supply water in the nation as a whole.

The water departments in each of these cities were contacted and asked to supply the following information for the years 1950 and 1960 and for the years 1965 through 1977:

1. Population served
2. The average amount of water supplied daily
3. The amount of energy consumed in supplying the water

In addition to this historic data, the water officials in each city were asked to project what the population served will be in the years 1980, 1990, and 2000 and to project whether or not their present water supply system will be able to meet the water demand in those years. In cases where the response to this question was negative, water officials were asked to specify what plans the city had made to develop new sources of water and what the estimated energy requirements of the new system will be.

Based on trends in the historic data, projected population figures, and each city's plans for its water supply system, estimates of the future water demand and the primary energy requirement to supply a unit of water were made. From these projections, the total annual primary energy consumption for the years 1980, 1990, and 2000 was calculated.

These projections indicate that the total annual amount of energy that will be required to supply water will decrease in St. Louis and New Orleans and will increase in Chicago, San Antonio, Denver, and Los Angeles. To determine the significance of the projected increases in Chicago, San Antonio, Denver, and Los Angeles, the percentage increases were compared to projected increases in domestic energy consumption for the nation as a whole. This comparison indicated that three of the cities, Los Angeles, San Antonio, and Denver, will have a higher rate of increase in their water-supply energy requirements than the national rate of increase of total energy consumption.

The results of this study indicate that there will not be a uniform change in the amount of energy required to supply water in these six cities. They do, instead, emphasize that there will be large regional differences in the amount of water energy required to supply water due primarily to population shifts to water-short areas of the country. This difference seems to indicate, therefore, that the amount of energy that will be needed to supply water in the future will be more a regional problem rather than a national concern.

The data used to characterize the energy required for sewage treatment were not compiled by survey but were provided by the federal Environmental Protection Agency (USEPA). A state-by-state listing of all treatment plants in use in 1977 divided among six types of treatment was provided along with a second listing of all treatment plants expected to be in operation in 1990. These lists were prepared from the USEPA's *1976 Needs Survey for Municipal Wastewater Treatments*. The types of plants were assigned an energy requirement based on a draft paper titled "Energy Conservation in Municipal Wastewater

Treatment," prepared by the firm of Culp/Wesner/Culp for the USEPA. The energy values presented by treatment type are the same for both 1977 and 1990. They include the primary energy needed to operate these plants plus the secondary or indirect energy consumed in the form of chemical additives, filter media, and other materials. This draft paper is scheduled for review and final publication in the next few months. The individual states in the nation are combined to form 12 geographical regions that roughly correspond to major water-basin areas in the country. The energy analysis presented contrasts these regions and also examines the treatment energy requirements for the nation as a whole. The significance of the growth rate in energy required to treat water is assessed by comparing it with the growth rate in national energy consumption between 1977 and 1990. Based on these USEPA data sources, the energy requirements for sewage treatment are growing much faster than energy consumption by the nation averaged over all consuming sectors. The energy growth rate varies among the 12 regions examined, but in all cases it exceeds the national increase in energy consumption.

This rapid growth rate in the energy required for sewage treatment is caused by two main factors: a large increase in the population served by sewers and the widespread introduction of more complex energy and material-intensive treatment strategies necessitated by more stringent water-quality standards. Although the energy required for sewage treatment in 1990 is less than one-half of one percent of the total national energy requirement, careful attention to cost minimization and energy conservation in sewage treatment will be an important concern if municipal budgets are to be balanced. Detailed analyses of the energy and material flows associated with specific types of treatment should be carried out and used in deciding among alternative plant designs. The USEPA is presently working on new review criteria that will ensure that energy and material requirements are critically examined before federal assistance funds are appropriated for plant construction. A disaggregated and detailed analysis of treatment options should also be used to examine the potential for energy conservation with special emphasis on use of methane gas, which is generated in some plants. Finally, the growing controversy over water-quality standards should be resolved with a careful determination of the environmental impact achieved with each additional increment of energy and material consumed in wastewater treatment.

The three irrigation projects examined in this study are located in Kern County, California; the Texas high plains; and San Carlos, Arizona. Published and unpublished data were provided by water agencies in these areas, and additional comments, estimates, and suggestions were relayed in phone conversations.

For Kern County data, the energy required to supply ground- and surface water has been estimated for each year between 1975 and 2000 inclusive. Based on historic trends, this area will experience growth in agricultural production and a decline in the water table because of groundwater withdrawals in excess of the recharge rate. These two factors will cause a 63 percent increase in the total primary energy required to supply irrigation water in the region between 1975 and 2000.

In the Texas high plains, virtually all water used for irrigation comes from the groundwater storage in a single aquifer. Withdrawals are much in excess of natural water recharge to the aquifer, and, consequently, increased primary energy is required to pump groundwater supplies from declining levels. In the short term, this increase will be partially offset by improved pumping efficiencies. Increased costs of irrigation and additional energy requirements will, nonetheless, force acreage out of agricultural production. The result will be a dramatic decrease in the total energy required to supply irrigation water in the area by the year 2000. Eventual depletion of the aquifer seems likely in the next century even with a general transition to dryland farming. Consequently, estimates are given of the energy that would be required to import water from outside the state for use in the high plains. An order of magnitude increase over the energy presently required per unit of water supplied is probable if water importation is undertaken.

In San Carlos, Arizona, acreage under irrigation will be relatively constant between now and the end of the century. A 40 percent increase in the total primary energy required to supply water for irrigation is expected to occur by 2000 as groundwater levels decline and additional energy is required to pump groundwater to the surface.

Because these areas of irrigation all lie in the arid Southwest, their projected energy requirements are probably upper bounds for energy needed to supply irrigation water in other parts of the nation. The energy growth in demand for energy in each of these irrigation areas is not significantly higher than the expected growth in energy consumption for the nation as a whole through the end of the century. Consequently, energy requirements for irrigation water in the United States are not expected to be critical through the year 2000.

After 2000, energy-intensive water-supply systems such as interbasin transfer and water reuse will be required to permit agriculture to continue in the Southwest. Sutdies of the long-term trade-offs among water consumption, energy consumption, and food production should be undertaken in consideration of future water-supply alternatives in these areas.

The results of the calculations presented in this paper are summarized in a table on page xii. In municipal water supply, the results indicate that there will be large regional differences in the amount of energy required to supply water.

The energy requirements for sewage treatment are increasing significantly in all areas of the country although there are huge regional differences among the growth rates. Between now and the year 2000, the total primary energy requirements for irrigation water will not increase faster than energy consumption by the nation as a whole. After 2000, however, energy requirements to supply water for irrigation in the arid Southwest may become severely large.

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SUMMARY OF RESULTS

WATER SUPPLY

City	Year	Primary Energy Required Per Unit of Water Supplied (MJ/mil gal)	Total Annual Primary Energy Consumption (MJ/year x 10^8)	Principal Energy Sources
Chicago	1976	10,557	39.5	Natural Gas
	2010	11,091	49.7	Coal, Electricity
St. Louis	1975	13,485	8.0	
	2000	13,485	5.5	Electricity
New Orleans	1976	12,601	5.7	
	2000	12,482	4.8	Electricity
Denver	1976	8,202	5.6	
	2000	11,597	14.1	Electricity
San Antonio	1976	15,422	5.7	
	2000	16,843	12.9	Electricity
Los Angeles	1975	5,562	10.3	Hydroelectric Power
	2000	8,933	18.1	

SEWAGE TREATMENT

Region	Year	Total Capacity (mgd)	Primary Energy Required Per Unit of Water Treated (MJ/mil gal)	Total Annual Primary Energy Consumption (MJ/year x 10^6)	Principal Energy Sources
U.S.	1977	30,722.5	12,454	139,651	Electricity Coal
	1990	56,514.5	14,006	292,295	Fuel Oil Natural Gas Methane

IRRIGATION

Region	Year	Primary Energy Required Per Unit of Water Supplied (MJ/mil gal)	Total Annual Primary Energy Consumption (MJ/year x 10^6)	Principal Energy Sources
Kern County	1975	18,479	20,502	Electricity
	2000	21,722	33,526	
Texas High Plains	1974	15,869	42,625	Natural Gas and Electricity
	2000	18,637	13,344	
San Carlos	1975	14,525	1,256	
	2000	21,234	1,814	Electricity

1 INTRODUCTION

This paper is presented as a pilot study designed to determine how critical the change will be in the demand for energy required to supply and treat water between now and the end of the century. To determine this change, we examined the primary energy requirements of three sectors of water supply and treatment: municipal water supply, municipal sewage treatment, and agricultural irrigation. In each area, we asked whether or not the growth rate in the amount of energy required to process water for these different uses will exceed the projected rate of increase in energy consumption for the nation as a whole.

At present, the energy required to supply water for irrigation and municipalities, combined with the energy required to treat domestic sewage, is estimated to be less than 2 percent of the total energy requirement.* Water is said to be a scarce resource, whose supplies are diminishing and becoming less accessible. To meet the demand for water, we may well require increasing amounts of energy and other physical resources. If this energy requirement rises at a rate significantly faster than the overall domestic demand for energy, the amount of energy that will be needed to supply and treat water will play an increasingly important role in the allocation of limited energy.

There is reason to believe that these energy requirements will increase significantly. New Environmental Protection Agency (EPA) quality standards for both sewage effluent and domestic water supplies will increase the energy required for water supply and treatment in many locations. Also, the depth to water tables is rapidly increasing in many areas of the United States and additional energy will be required to pump this water to the surface. Demographic shifts are accelerating the demand for water, especially where water is already scarce. More energy-intense water supply systems such as interbasin transfers, desalination plants, and water reuse projects will need to be developed to support the growth in these regions.

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*Based on upper bound energy estimates compiled for this paper, on EPA sewage treatment data, and on 1970 water withdrawals for irrigation listed in U.S. Geological Survey Circular 676.

The estimate of energy requirements over time for water supply, sewage treatment, and irrigation are based on data compiled by survey form, by telephone communication with municipal water experts and irrigation specialists, and from both published and draft materials. Many of the numbers used in this report are only estimates, and many of the extrapolations of future energy requirements incorporate simplifying assumptions. The method followed for calculating the energy requirements is described in detail, making clear the limitations of the data. The emphasis is less on very accurate data than on likely trends exhibited over time in the change of energy requirements and, most important, on determining what aspects of the water-related energy question must be understood better.

The changing patterns of energy consumption detailed in the text for water supply and sewage treatment are compared to available estimates of the present and future energy demands of the nation. Several projections of the growth in national energy consumption are available. All of them invoke simplifying assumptions with regard to the general health of the economy, energy prices, rates of extraction of fuel reserves, and possible governmental measures to allocate and regulate energy supplies. In this paper, estimates of energy consumption over time in the United States are taken from the November 1974 *Project Independence Report* of the Federal Energy Administration (FEA).

In the summary volume of that FEA report are several tables titled "United States Total Gross Consumption of Energy Resources by Major Sources and Consuming Sectors." Tables P-5 through P-16 present FEA projections of domestic energy consumption under different scenarios. Energy use in each of the tables is projected for five consuming sectors of the United States economy: household and commercial, industrial, transportation, electrical generation, and synthetics. The differences among the scenarios in these tables arise from different estimates of the price of oil ($7 or $11 per barrel [bbl]), whether or not the supply of energy will be accelerated, and whether or not energy conservation measures will be undertaken. Depending on the assumptions made, the anticipated increase in the domestic energy requirement between 1971 and 1985 ranges from 22 to 32 percent in these tables. The 22 percent increase represents a scenario based on Table P-14, in which oil prices are $11 per bbl, conservation is promoted, and no effort is made to accelerate the energy supply. The higher 32 percent increase is a "no conservation" scenario derived from Table P-5 of the report.

For years after 1985, the *Project Independence Report* discusses the growth rate of energy consumption in Part III of Chapter III: "Long-Term Energy Projections and Their Implications." Two long-term supply strategies are characterized. The first of these, called the "Base Case," predicts that overall energy consumption will increase 2.5 percent per year from 1985 through 2000. This scenario assumes that energy conservation measures will not be widely implemented. The second strategy, called the "Conservation-Major Shift," estimates a 1.6 percent increase in overall energy consumption in each year from 1985 through 2000 with more stringent conservation measures imposed. Under the "Base Case" strategy the domestic demand for energy will increase approximately 69 percent between 1977 and 2000 assuming that the increase between 1977 and 1985 is the 32 percent of the "no conservation" scenario. Under conditions of the "Conservation-Major Shift," a 46 percent increase in energy consumption is projected from 1977 through 2000, assuming the more modest 22 percent increase between 1977 and 1985. Summarized below are the FEA projected changes in national energy consumption for various time periods under the conservation and base case scenarios.

Conservation Scenario (based on *Project Independence Report*, Table P-14, and "Conservation-Major Shift Case" after 1985)

1975-2000	49 percent increase in gross consumption of energy resources in the United States
1977-2000	46 percent increase in gross consumption of energy resources in the United States
1977-1990	30 percent increase in gross consumption of energy resources in the United States

No Conservation Scenario (based on *Project Independence Report*, Table P-5, and "Base Case" after 1985)

1975-2000	75 percent increase in gross consumption of energy resources in the United States
1977-2000	69 percent increase in gross consumption of energy resources in the United States
1977-1990	44 percent increase in gross consumption of energy resources in the United States

Throughout this paper these FEA projections of the change in total gross consumption of energy resources averaged over five consuming sectors of the United States economy will be used as a benchmark against which to judge the significance of projected increases in the energy required to supply water and treat sewage.

All the energy calculations presented in this study present the energy requirements as the total primary energy required to operate the water systems examined. "Primary energy" represents the energy embodied in the directly burned fossil fuels and in the primary fuels required to generate electricity consumed in operation of these systems. The primary energy is sometimes referred to as the thermal equivalent. It includes the fuel necessary to run the electrical generating facilities and to transmit the electricity along cables and wires in addition to the direct energy delivered for use at the on-site electrical outlets. The direct energy and primary energy of fossil fuels are equivalent and, strictly, are the heats of combustion of the fuels. For electricity, however, there is an essential distinction between the primary and direct energy per kilowatt hour (kwh). The direct energy characterizes only the usable energy obtained from each kwh and excludes the energy "losses" in electrical generation and transmission. The unit of energy in common terms for electricity, the kilowatt hour, is equivalent to 3.6 megajoules (MJ), the International Standard unit used in this analysis. The primary energy required to generate 1 kwh of electric energy has dropped during the past fifty years. In 1929 each kwh of electric energy required, on the average, 25.89 MJ of primary energy, while in 1970 each kwh represented primary energy equivalent to only 11.11 MJ. For the year 1970, the primary energy equivalent per kwh (11.11 MJ) is approximately three times that of the direct energy equivalent (3.6 MJ). We assumed a figure of 11.11 MJ of primary energy per kwh of delivered electric energy for the projected energy requirements in this study.

Another energy input often included in energy studies is the indirect or secondary energy requirement of a system. which refers to the energy embodied in raw and manufactured materials or in other goods and services consumed during production. For water supply and water treatment, chemical additives such as chlorine, alum, and lime are the main indirect energy requirements. The energy of capital is also included in some studies and characterizes the energy content of materials such as steel, wood, and cement used in construction of a plant or facility.

In this present study, capital energy requirements have been excluded from all analyses presented. Secondary energy requirements are not included in the water supply or irrigation scenarios, but they are taken into account in the energy calculations for sewage treatment, where they add a small but not negligible contribution.

2 WATER SUPPLY

Water and energy are linked resources. Although we are more accustomed to thinking in terms of harnessing water for energy production than in terms of using energy for water supply, energy is an important factor in acquiring, treating, and distributing the water we consume. The objective of this chapter is to determine how much energy is presently required to supply water and whether or not this energy requirement will increase significantly by the year 2000. Ultimately, our aim is to determine whether or not the energy needed to supply water will constitute a significant portion of our total national energy budget in future years.

The original goal of this study was to determine how much energy is needed to supply water on a national basis by examining the energy requirements of groundwater and surface-water usage in the major water regions of the country. However, in accommodating the scale of the project to its level and manner of support, we have limited the supply study to the energy requirements of the water supply systems of six large cities located in different areas of the country. Data presented in a 1962 (USGS) publication about the water supply systems of the country's 100 largest cities indicate that the 10 cities selected are large consumers of water.[1]

The energy requirements of these urban areas provide an indication of the extent and location of future increases in the amount of energy required to supply water in the nation as a whole.

The cities we initially chose to examine in this study were Boston, Chicago, St. Louis, New Orleans, Los Angeles, Denver, Miami, San Antonio, Phoenix, and Houston. Boston, Chicago, St. Louis, New Orleans, and Denver all obtain their water supply from surface sources. Miami and San Antonio are the two largest cities in the country that rely entirely on groundwater as their source of supply, and Los Angeles, Houston, and Phoenix draw their water from both surface- and groundwater sources.

The water departments in each of these cities were contacted and asked to complete a survey from. Basically, the survey from (Appendix 1) asked for the following information for the years 1950, 1960, and 1965 through 1977:

1. Population served
2. The average amount of water supplied daily
3. the amount of energy consumed in supplying the water

In addition to this historic data, we asked the water officials in each city to project what population they will serve in the years 1980, 1990, and 2000 and to project whether or not their present water-supply system would be able to meet the water demand in those years. In cases where the response to this question was negative, we asked what plans the city had made to develop new sources of water and what the estimated energy requirements of the new system would be.

Of the 10 cities contacted, eight responded to our survey, and six (Chicago, Denver, Los Angeles, New Orleans, San Antonio, and St. Louis) were able to supply us with the data we requested. Phoenix and Houston responded but were unable to provide energy data.

The data were analyzed as follows. First, the city's historic per capita consumption rates were studied and used to project what the future per capita consumption rates will be. These projections were then multiplied by the projected population figures to estimate what the future water demand in each of these cities will be. Next, projections were made of the future energy requirement to supply a unit of water. These projections were based on trends in the historic data and on the city's plans for its water supply system. Finally, the total annual energy consumption for the years 1980, 1990, and 2000 was estimated from the projected water demand and the projected energy requirement. As the results presented in the following sections indicate, this method of analysis is sensitive to two factors: (1) a change in the city's population that would affect the water demand and (2) major changes in the city's water supply system that would affect the energy requirement to supply a unit of water.

Descriptions of the water supply systems in the cities of Chicago, St. Louis, Denver, New Orleans, San Antonio, and Los Angeles and the projected energy requirements to supply water in these six cities are presented in the following sections. It should be emphasized that the energy consumption projections presented in this study are only rough estimates based on particular sets of assumptions. No attempt was made to explore more than one or two projections for each city, consistent with the pilot character of this study.

Chicago

Although Chicago is located near an abundant source of water, maintaining a clean and safe drinking water supply has constituted a major problem throughout much of the city's history. Early settlers to the area first drew their water directly from the Chicago River, but, as the river became polluted, they turned to Lake Michigan as their source of supply. Because of Chicago's rapid growth, sanitary problems worsened. More and more sewage was dumped into the Chicago River, which flowed into Lake Michigan, endangering the city's water supply. It was not until the turn of this century, when the Chicago Sanitary and Ship Canal was constructed, permanently reversing the flow of the Chicago River, that the city of Chicago was able to procure a safe source of water supply.

Chicago, the second largest consumer of water in the country (New York City is the largest), now draws its water supply from Lake Michigan through intake cribs located two to three miles offshore. Although Chicago has a relatively clean source of surface water compared to other major cities, it still must treat the water from its intakes. The city maintains two water treatment facilities on the lakefront: the Central Filtration Plant, which has a rated capacity of 1700 million gallons per day (mgd), and the South Water Filtration Plant, which has a rated capacity of 900 mgd. The Central

Filtration Plant employs a treatment series of chemical addition, coagulation, settling, rapid-sand filtration, and chlorination.

Electricity, fuel oil, coal, and natural gas are used to supply the energy required to operate Chicago's water supply system. In 1976, for example, the system consumed 27,594 tons of coal, 38,679 gallons (gal) of fuel oil, 22,419 therms of natural gas, and 72,862,000 kwh of electricity. The primary energy of these fossil fuels and electrical inputs gives an energy requirement of 10,557 megajoules per million gallons (MJ/mil gal). (Primary energy requirements are calculated throughout this study.) If, instead, the direct energy requirement, which excludes the energy required to generate and transmit power, is calculated, the 1976 energy requirement for the Chicago system becomes 9,092 MJ/mil gal, which is approximately 14 percent lower than the primary energy calculation.

To comply with new clean air standards, Chicago's Water Department began phasing out its coal usage in 1969. A conversion was made to natural gas. However, because of the developing shortage of natural gas, the water department has halted its program to totally phase out its coal usage. The water supply system still uses coal to produce energy, but not to the extent that it was used in the past.

In 1976, the city of Chicago's water division served 4,664,000 people. Unlike departments in most of the other cities examined in this study, Chicago's water department supplies water to areas outside the city limits. For example, of the 4,664,000 people served in 1976, 3,369,000 people resided in Chicago, while 1,295,000 of the people served lived in the outlying suburbs. Presently, 74 suburban communities are supplied with water by Chicago's water supply system. These communities are listed in Table 1 and can be located on Figure 1.

While the population of Chicago proper is expected to remain approximately constant, the amount of water supplied by the city is expected to increase in the future. Most of the suburban areas surrounding Chicago now obtain their water supplies from groundwater. But as the supply of water in the aquifers in the suburban regions diminishes, it is anticipated that more suburbs will obtain their water supply from Lake Michigan via the Chicago water system.

Table 1

Suburban Communities Presently Served by the Chicago Water Supply System

---

Alsip
Bedford Park
Berkeley
Berwyn
Blue Island
Bridgeview
Broadview
Brookfield
Burnham
Calumet City
Calumet Park
Central Stickney S.D.
Chicago Ridge
Cicero
Countryside
Crestwood
Des Plaines
Dixmoor
Dolton
East Hazel Crest
Elmwood Park
Evergreen Park
Forest Park
Forest View
Franklin Park
Garden Homes S.D.
Golf
Harvey
Harwood Heights
Hazel Crest
Hickory Hills
Hillside
Hodgkins
Hometown
Justice
La Grange Park
Leyden Township
Lincolnwood
Lyons
Markham
Maywood
McCook
Melrose Park
Merrionette Park
Midlothian
Morton Grove
Niles
Norridge
Northlake
North Riverside
Oak Forest
Oak Lawn
Oak Park
Palos Heights
Palos Hills
Park Ridge
Phoenix
Posen
Riverdale
River Forest
River Grove
Riverside
Robbins
Rosemont
Schiller Park
South Holland
South Stickney S.D.
Stickney
Stone Park
Summit
Tinley Park
Westchester
Willow Springs
Worth

Source: Chicago Department of Water and Sewers, 1976. *Annual Report--Operating Statistics*, p. 15.

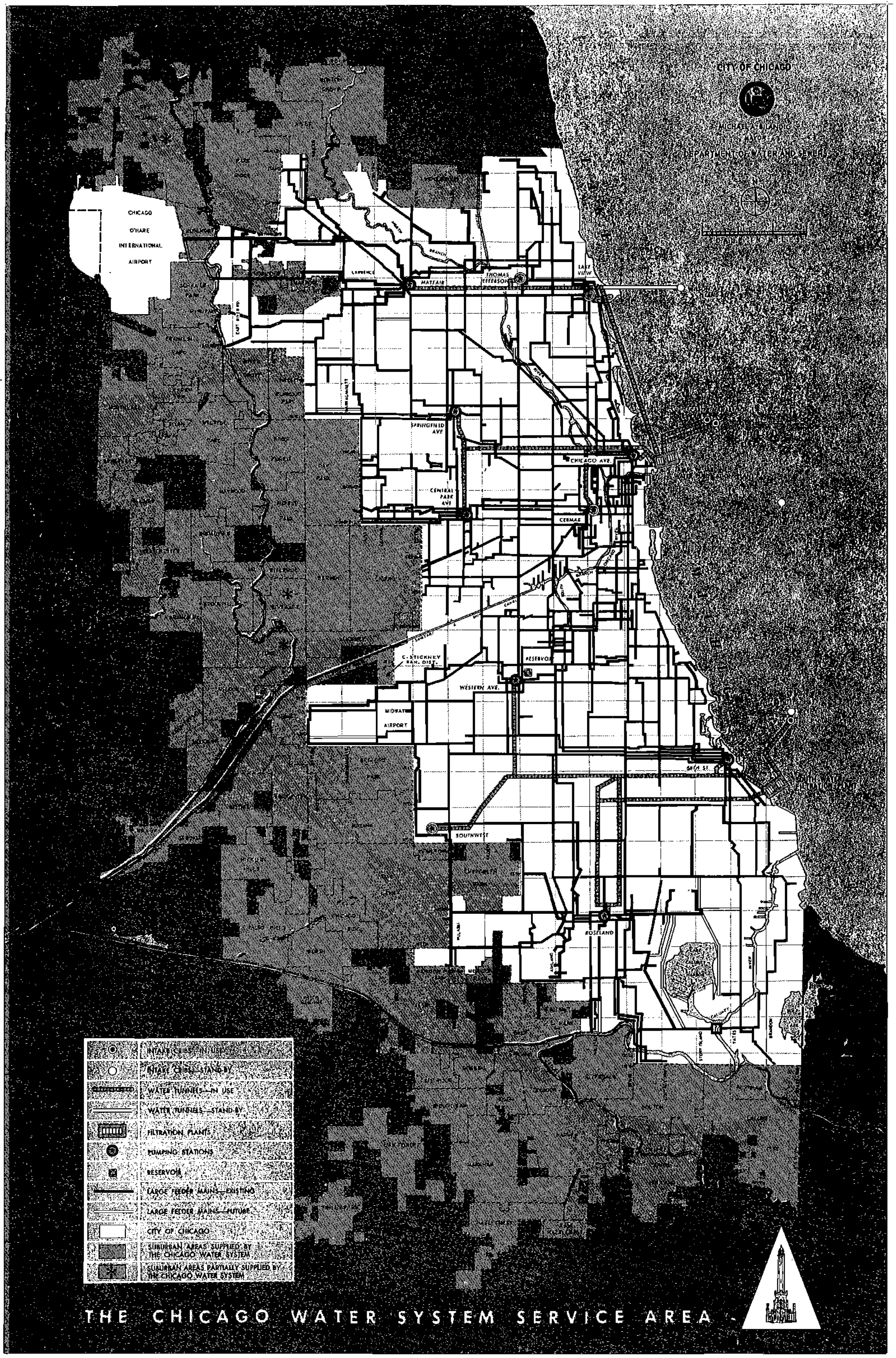


Figure 1. Chicago water supply system.

Proposed plans indicate that the water would be treated by Chicago and pumped out to the suburbs. Distribution would be the responsibility of the suburban communities. Exactly how many suburbs will be added to the Chicago water supply system in the future is unknown. By 1980, the number to be added is at least 18 because that many communities have already contracted with the city for water.

Water and energy consumption data for the years 1965 through 1977 were collected from the Chicago Department of Water and Sewers. These data were presented in Table 2. Projections were based on these historic data and a study done for the Northeastern Illinois Planning Commission by the Keifer and Associates engineering firm.

Table 2

Historic Water Consumption and Primary Energy Requirements for the Chicago Water Supply System

Year	Average Amount of Water Supplied (mgd)	Total Energy Consumption (MJ/day x 10^6)	Energy Required per Unit of Water Supplied (MJ/mil gal)
1965	991	11.27	11,372
1966	1,011	11.61	11,484
1967	1,005	11.54	11,483
1968	1,024	11.79	11,514
1969	1,023	11.50	11,241
1970	1,035	11.75	11,353
1971	1,028	12.34	12,004
1972	1,011	11.21	11,088
1973	1,041	10.81	10,384
1974	1,027	10.60	10.321
1975	1,021	10.95	10,725
1976	1,024	10.81	10,557

The Keifer report develops a number of scenarios regarding additional suburban supply, two of which are utilized in this study. Plan 1 presents the minimum number of additional suburbs to be supplied by the Chicago water supply system. These suburbs are the 18 cities which have already contracted with the city. Plan 2 presents the maximum number (40) of additional suburbs to be supplied. Tables 3 and 4 present these two plans, with the communities to be served and the projected amount of water allocated to each. These two plans were employed in this study to establish a range for projected energy requirements.

To estimate the future amount of water that will be supplied to the present users of the Chicago water supply system, the average daily supply (mgd) for 1965 through 1976 was extrapolated using a linear regression. Because estimates of the projected population to be served were not available from the City Department of Water and Sewers, the consumption in mgd was extrapolated in lieu of per capita consumption. The projected water demand of the present users of the Chicago water supply system and the projected amount of water to be allocated to suburban users under Plans 1 and 2 are shown in Table 5.

The projected energy requirement per unit of water supplied for the present water supply system (serving the city and 74 suburbs) was estimated to be the same as the 1976 energy requirement (10,557 MJ/mil gal). This projection was based on an analysis of the 1965 through 1976 energy consumption data. Beginning in 1969, the energy required per unit of water supplied began to decrease because of the conversion from coal to natural gas, a more efficient source of energy. But to extrapolate this energy data linearly would capture a downward trend in the energy requirement that is not likely to continue into the future. In light of these facts, the 1976 energy requirement was assumed to be the best estimate of the future energy requirement of supplying a unit of water.

The additional energy that will be needed to transport water to outlying suburbs according to Plans 1 and 2 was calculated from the following relationship:

$$\left(\frac{\text{ft-headloss}}{\text{mile}}\right)(\text{distance of transport})\left(\frac{53\text{ MJ}}{\text{mil gal lifted one ft}}\right) = \frac{\text{MJ}}{\text{mil gal}}$$

The number of feet of headloss per mile was taken to be 7.5, which is the

Table 3

Plan 1--Projected Water Allocations for Outlying Chicago Suburbs

Community	Average Daily Allocation (mgd) 1980	1996	2010
Addison	0.83	5.29	5.84
Arlington Heights	5.68	9.02	9.79
Bensenville	2.41	2.88	3.05
Buffalo Grove	1.16	3.30	3.83
Carol Stream	1.08	4.69	6.18
Downers Grove	3.00	8.94	10.63
Elk Grove Village	5.65	8.68	10.71
Elmhurst	5.91	8.47	8.88
Glendale Heights	0.80	2.99	3.23
Hoffman Estates	2.83	5.57	6.22
Lombard	4.11	5.79	6.29
Mount Prospect	2.27	6.13	6.60
Oak Brook	2.73	4.33	4.51
Palatine	2.93	8.00	8.06
Rolling Meadows	0.95	3.31	3.67
Schaumburg	3.56	10.25	12.90
Villa Park	1.76	3.36	3.62
Westmont	0.68	2.08	2.36
Total	48.34	103.08	116.37

Source: Keifer and Associates, Inc. 1977. "Supplement to the Regional Water Supply Planning Study--A Phased Program for Northwest Cook and DuPage Counties." *Alternative Water Supply Systems*, ch. II., p. II-7.

Table 4

Plan 2--Projected Water Allocations for Outlying Chicago Suburbs

	Average Daily Allocation (mgd)		
Community	1980	1995	2010
Addison	0.83	5.29	5.84
Arlington Heights	5.68	9.02	9.79
Bensenville	2.41	2.88	3.05
Bloomingdale	0	2.39	3.06
Buffalo Grove	1.16	3.30	3.83
Burr Ridge	0	1.54	1.94
Carol Stream	1.08	4.69	6.18
Clarendon Hills	0	0.88	0.88
Darien	0	2.62	3.13
Downers Grove	3.00	8.94	10.63
Elk Grove Village	5.65	8.68	10.71
Elmhurst	5.91	8.47	8.88
Glendale Heights	0.80	2.99	3.23
Glen Ellyn	0	4.44	4.95
Hanover Park	0	4.22	4.67
Hinsdale	0	2.92	3.13
Hoffman Estates	2.83	5.57	6.22
Itasca	0	1.85	2.14
Lisle	0	5.00	6.16
Lombard	4.11	5.79	6.29
Lombard Heights	0	0.20	0.20
Mt. Prospect	2.27	6.13	6.60
Naperville	0	10.87	13.38
Oak Brook	2.73	4.33	4.51
Oak Brook Terrace	0	1.15	1.26
Palatine	2.93	8.00	8.06
Prospect Heights	0	2.09	2.31
Rolling Meadows	0.95	3.31	3.67
Roselle	0	2.42	2.60
Schaumburg	3.56	10.25	12.90
Streamwood	0	3.90	4.47
Villa Park	1.76	3.36	3.62
Waycinden	0	0.49	0.57
Westmont	0.68	2.08	2.36
Wheaton	0	6.45	7.50
Wheeling	5.68	2.78	2.98
Willowbrook	0	0.89	1.02
Winfield	0	0.90	1.21
Wooddale	0	1.56	1.75
Woodridge	0	2.30	2.58
Total	48.34	165.94	188.26

Source: Keifer and Associates, Inc. 1977. "Supplement to the Regional Water Supply Planning Study--A Phase Program for Northwest Cook and DuPage Counties." *Alternative Water Supply Systems*, ch. II., p. II-11.

Table 5

Projected Water Demand for the Chicago Water Supply System

Year	Present Users (mgd)	Additional Suburbs Plan 1 (mgd)	Additional Suburbs Plan 2 (mgd)
1980	1043.2	48.34	48.34
1995	1077.2	103.08	165.94
2010	1111.3	116.37	188.26

average value used by the Texas Water Development Board. This value assumes level horizontal transport, which is characteristic of the Chicago area. A more accurate value for the amount of headloss per mile would depend on structural elements of the system and could only be determined by testing the system in operation.

The additional distance the water would have to be transported was estimated to be approximately 14 miles (mi) for both Plans 1 and 2. The total distance of transport from the lakefront treatment facilities to the suburbs would then be approximately 30 mi, into DuPage County.

The energy to transport 1 mil gal one foot was calculated to be 53 MJ. This estimate was based on a 65 percent efficiency of electrical pumping.

The projected energy requirement per unit of water supplied for the present water supply system and the additional transport of water to outlying suburbs are given in Table 6. The fourth column of the table presents the total energy requirement per unit of water supplied for Plan 1. This projection was derived from a weighted average of columns two and three. The total energy requirement times the projected amount of water to be supplied under Plan 1 gives the total annual energy consumption listed in the last column. The same projections for Plan 2 are presented in Table 7. The historic and projected energy requirements and total annual energy consumption are illustrated in Figures 2 and 3.

The results of the calculations for Plan 1, which represents the minimum number of suburbs to be added to the city water supply system, indicate a

Table 6

Projected Primary Energy Consumption Based on Plan 1 for the Chicago Water Supply System

Year	Projected Energy Requirement of Present System (MJ/mil gal)	Projected Energy Requirement to Transport Water to Suburbs (MJ/mil gal)	Weighted Average Energy Requirement Per Unit of Water Supplied (MJ/mil gal)	Projected Total Annual Energy Consumption (MJ/Year x 10^8)
1980	10,557	5,565	10,793	43.0
1995	10,557	5.565	11,049	47.6
2010	10,557	5,565	11,091	49.7

Table 7

Projected Primary Energy Consumption Based on Plan 2 for the Chicago Water Supply System

Year	Projected Energy Requirement of Present System (MJ/mil gal)	Projected Energy Requirement to Transport Water to Suburbs (MJ/mil gal)	Weighted Average: Energy Requirement per Unit of Water Supplied (MJ/mil gal)	Projected Total Annual Energy Consumption (MJ/year x 10^8)
1980	10,557	5,565	10,793	43.0
1995	10,557	5,565	11,306	51.3
2010	10,557	5,565	11,365	53.9

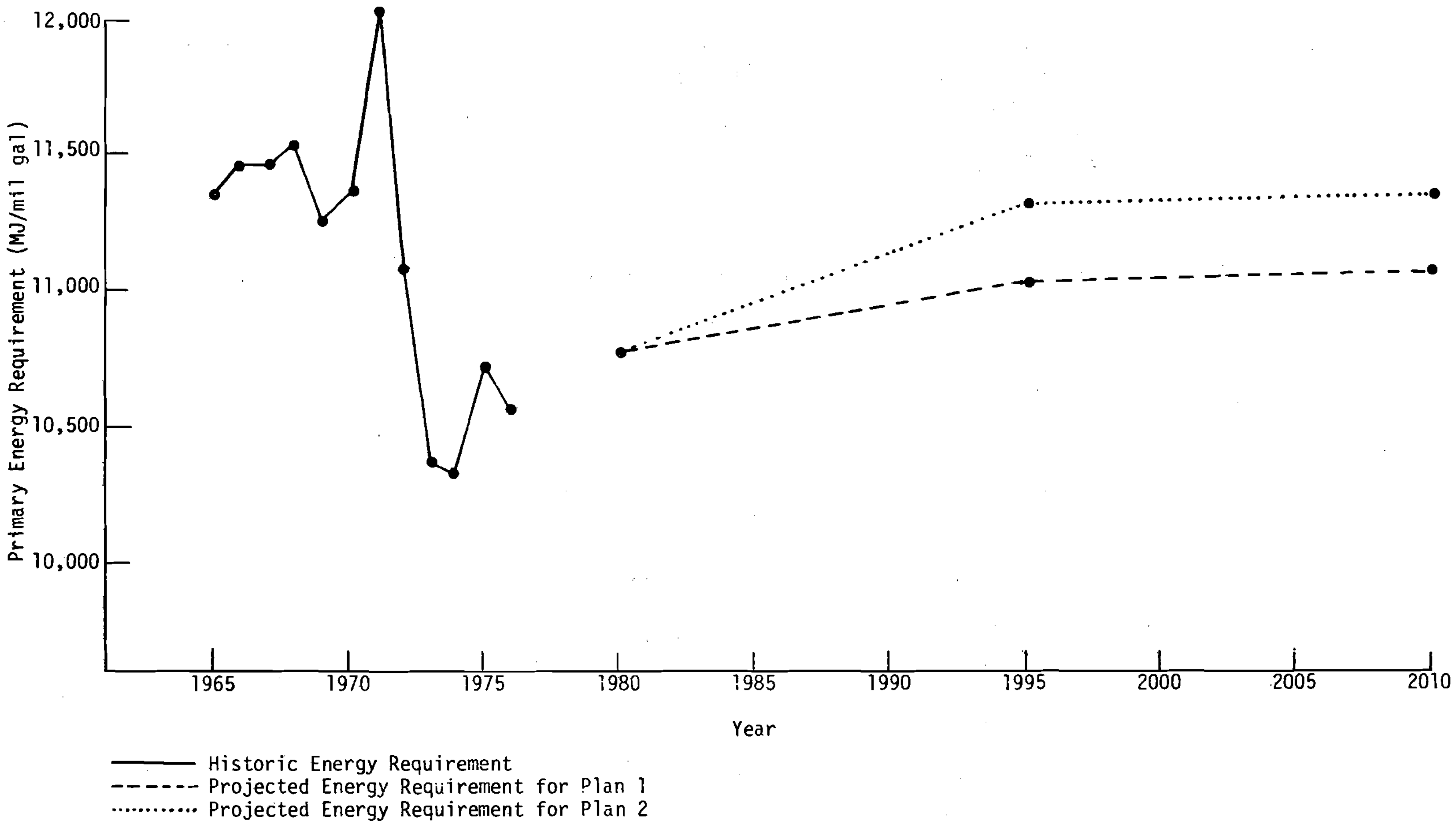


Figure 2. Historic and projected primary energy requirement per unit of water supplied for the Chicago water supply system.

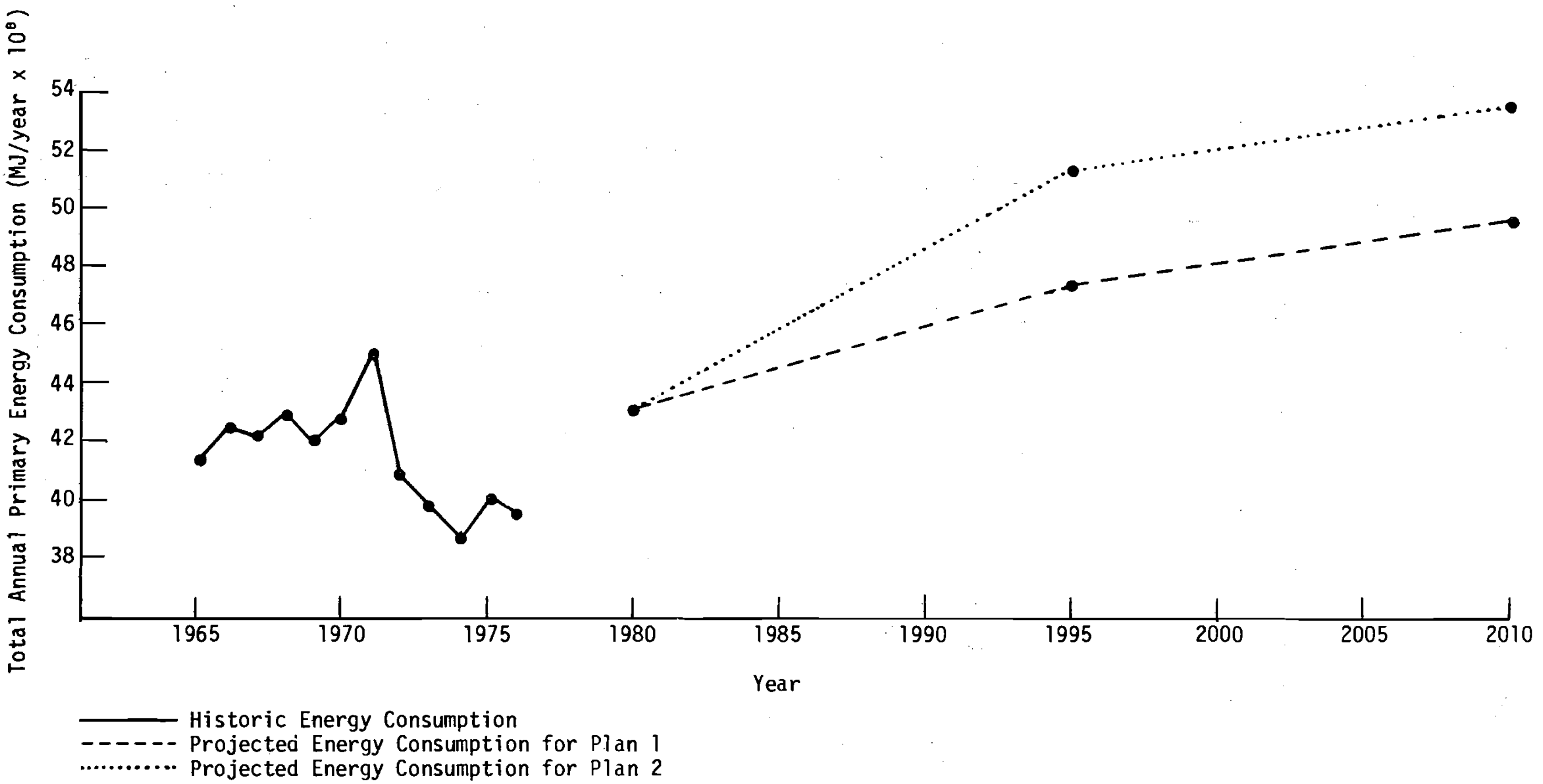


Figure 3. Historic and projected total annual primary energy consumption for the Chicago water supply system.

5.1 percent increase in the MJ/mil gal requirement and a 25.8 percent increase in the total annual energy consumption between the years 1976 and 2010. The calculations for Plan 2, which represents the maximum number of suburbs to be supplied in the future, indicate a 7.7 percent increase in the MJ/mil gal requirement and a 36.5 percent increase in the total annual energy consumption between the years 1976 and 2010. If the results of Plans 1 and 2 give a reasonable range, then we can project about a 6.4 percent increase in the MJ/mil gal requirement, and a 31.1 percent increase in the total annual energy consumption.

Although the projections presented in this study are rough estimates of future energy requirements, all indications are that the amount of energy required to supply water in Chicago will increase in future years. Assuming the population of Chicago proper remains stable, the significance of the increase will depend on two factors: the type of fuel the water department will use to operate its system and the number of additional suburbs that will be supplied with water by the city.

St. Louis

The city of St. Louis depends entirely on surface sources for its water supply. A major portion (71 percent) of St. Louis's water is drawn from the Mississippi River; the rest is taken from the Missouri River. The water is purified at two treatment facilities: the Chain of Rocks plant (located on the Mississippi River) and the Howard Bend plant (located on the Missouri River). The larger plant, the Chain of Rocks, employs a treatment series of chemical addition, coagulation, settling, and rapid-sand filtration.

Like the city of New Orleans further downstream, St. Louis has an abundant supply of water. Water officials suggest that because of St. Louis's location, water quality is less of a problem than it might be elsewhere on the Mississippi. St. Louis's intake is just below the point where the Missouri River converges with the Mississippi so that the Mississippi water has been greatly diluted. At the city's intake on the Missouri River, the major water-quality problem is turbidity resulting from agricultural runoff, which water officials view as a lesser problem than industrial and municipal contaminants.

The population of St. Louis proper has declined rather drastically from 1950 to the present. Census Bureau statistics show that St. Louis had a population of 856,796 in 1950 as compared to the 515,000 people the city water division now serves. Flight to the suburbs accounts for much of St. Louis's decline in population. The water demand just outside of St. Louis has greatly increased, but since the city only supplies water to areas that are within the city limits (and expects to continue to do so in the future), the water demand in the city is declining. Industry, however, has remained in the city, and it presently consumes approximately 60 percent of the total water supply.

St. Louis anticipates no scarcity of water in the future, as it plans to continue to use its present sources. Also, the amount of water the city will supply is expected to decline. Projections indicate that St. Louis's population will continue to decline, although not as fast as in recent years (see Table 8). Industry may also join the flight to the suburbs. It is unlikely that a great deal of industry will be moving into the city.

Table 8

Projected Population to Be Served by the St. Louis Water Supply System

Year	Projected Population
1980	500,000
1990	485,000
2000	480,000

St. Louis's water division supplied energy data for the years 1965 through 1975. Table 9 shows the average daily water demand for each year and the energy required per unit of water supplied. The energy data presented in Table 9 are in terms of primary energy requirements. In 1975, for example, the St. Louis water supply system consumed 72,000,000 kwh of electricity, which gives a primary energy requirement of 13,485 MJ/mil gal. If, instead, the direct energy requirement is calculated, the requirement is only 4,373 MJ/mil gal, which is approximately 68 percent lower than the primary energy calculation.

Prior to 1973, the energy required to operate the water system was supplied by a combination of purchased electricity and coal. To comply with new

Table 9

Historic Water Demands and Primary Energy Requirements of the St. Louis Water Supply System

Year	Average Amount of Water Supplied (mgd)	Total Primary Energy Consumption (MJ/day x 10^6)	Energy Required per Unit of Water Supplied (MJ/mil gal)
1965	182.8	3.82	20,897
1966	182.9	3.74	20,448
1967	185.7	3.89	20,947
1968	195.3	3.99	20,430
1969	196.7	4.30	21,860
1970	186.5	3.80	20,375
1971	176.4	3.64	20,634
1972	176.1	3.06	17,376
1973	175.5	2.29	13,048
1974	170.0	2.31	13,588
1975	162.4	2.19	13,485*

*This figure was estimated to be the future energy requirement to supply a unit of water.

clean air standards, coal was gradually phased out (starting in 1969) so that in 1973 all the operating energy was provided by purchased electricity. As the data in Table 9 demonstrate, the primary energy needed to supply a unit of water has declined. Electricity has been a more efficient means of supplying energy than coal at the point of end use.

Because of the sharp decline in the energy required per unit of water supplied from 1965 through 1975, a straight-line extrapolation of the data does not give a realistic future energy requirement. Therefore, the energy needed to treat and supply a unit of water in future years was taken to be the same as the energy required in 1975. This estimate was based on two assumptions:

1. Since the present system of supplying water is to be maintained, and no new sources developed, it is unlikely that the energy requirement will increase.

2. The data for the years 1973, 1974, and 1975 seem to indicate a leveling out of the energy requirement once the conversion from coal to electricity was completed.

To project the amount of water that will be supplied in future years, the average mgd for the years 1965 through 1975 was extrapolated by linear regression. The projected mgd was then multiplied by the energy requirement for 1975 and 365 days to give the total annual energy consumption. As the results in Table 10 demonstrate, the amount of waterthat the city will supply in the future will be less than at present, and thus the amount of total annual energy consumption will also be less. This decline is illustrated in Figure 4. Comparison between the years 1975 and 2000 indicates a 32 percent decrease in total annual energy consumption.

Table 10

Projected Water Demand and Primary Energy Consumption of the St. Louis Water Supply System

Year	Water Demand (mgd)	Energy Required per Unit of Water Supplied (MJ/mil gal)	Total Annual Energy Consumption (MJ/year x 10^8)
1980	155.25	13,485	7.64
1990	133.15	13,485	6.55
2000	111.05	13,485	5.47

Because the amount of water St. Louis supplies has not declined as rapidly as its population (because industry has remained in the city), per capita consumption figures were not used to project the future water demand. Extrapolation of past per capita consumption rates would skew the projection upward in a manner inconsistent with the expected decline in the number of people to be served.

If one were to assume that the per capita consumption rate would be the same in the future years that it was in 1974 (318 gal/person/day) and that the energy requirement per unit of water were also to remain approximately the same, then the total annual energy consumption would also remain essentially the same, decreasing slighly in proportion to the expected decrease in population.

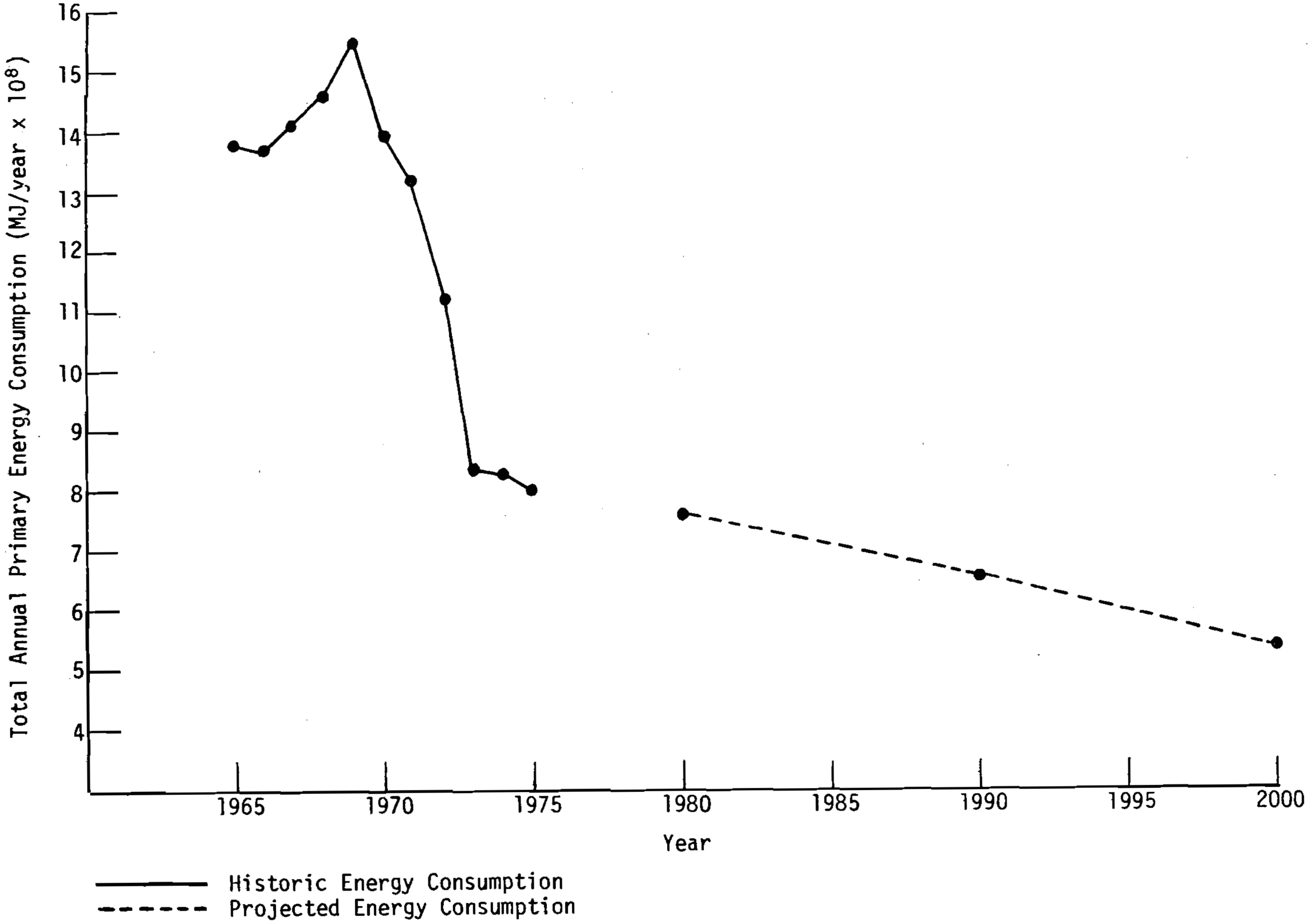


Figure 4. Historic and projected total annual primary energy consumption for the St. Louis water supply system.

Based on observed trends in the data collected and on conversations with St. Louis water officials, it seems reasonable to conclude that the energy required to operate St. Louis's water supply system will not increase significantly in the future. Given the assumptions made in this study, the amount of energy consumed will actually decrease by 32 percent (an upper limit) or to a figure slightly lower than what it is now.

New Orleans

New Orleans presently obtains its water supply from the Mississippi River. With this readily available source of water close by, the city does not face any shortage of water, although water quality is a major consideration. Because it is located at the mouth of the Mississippi River, New Orleans intakes water that has been polluted by many users upstream. For this reason (and because New Orleans does have a significant withdrawal rate compared with other United States cities), we chose to examine the energy requirements of the New Orleans water supply system as an example of a city with a relatively low quality source of water. Ultimately, our objective was to compare this systems's energy requirement to supply and treat a unit of water with the energy requirement for the city of Chicago, which has a relatively clean source of water. Both employ the same treatment process. The purpose of the comparison was to determine whether the energy requirement increases significantly if the quality of water declines.

The city of New Orleans treats its water at the Carrollton Purification Plant, a 232 mgd capacity plant located on the east bank of the Mississippi River. (The Algiers Treatment Plant, a much smaller facility located on the west bank of the river, serves the western part of the city. It has a rated capacity of 15 mgd.) The Carrollton plant employs a series of chemical addition, mixing, sedimentation, and rapid sand filtration in its treatment process. Special equipment adds activated carbon slurry when it is necessary to control water quality.

The total amount of energy required to operate the system is the sum of the energy consumed in pumping the water from the river to the treatment plant, treating the water and distributing it through the city. This energy is provided by electrical power, generated on site by a city-owned power plant.

New Orleans only supplies water to areas within the city's limits. Most of the industries in the city have drilled their own wells, so only a few industries obtain their water from the public supply. Thus, the population of the city is the real indicator of consumption. Data indicate that New Orleans's population has been declining since 1960, and projections show this trend continuing into the future. The amount of water supplied in future years is likely to be less than at present.

New Orleans plans to continue using the Mississippi River as its sole source of water. There is a considerable amount of groundwater available in this area, raising the question: If in the future the water quality of the Mississippi River makes it prohibitively expensive to use, will a conversion to groundwater occur? The New Orleans City Water and Sewer Board does not anticipate this happening. The city plans to continue using the Mississippi River as its source of water supply far into the future.

The New Orleans City Water and Sewer Board provided consumption and energy data for the years 1973 through 1976. The power plant operated by the city supplies power to three divisions of the city's water system: water treatment, sewage treatment, and drainage pumping. Although the city supplies its own power, the data we obtained were limited because prior to 1973 the data were not differentiated as to where the energy supplied to the whole system was being consumed, e.g., water treatment, sewage treatment, or drainage pumping. However, based on the data that were available and on conversations with New Orleans water officials, an attempt was made to characterize the energy requirement of the present water supply system and to project what it will be in the future.

The water demand and energy data for the years 1973 through 1976 are presented in Table 11. The last column of the table indicates the primary energy requirement per unit of water supplied. In 1976, for example, the New Orleans water supply system consumed 50,979,000 kwh of electricity, giving a primary energy requirement of 12,601 MJ/mil gal. The direct energy requirement for 1976, by contrast, would be 4,088 MJ/mil gal, which is approximately 68 percent lower than the primary energy requirement.

Table 11

Historic Water Demands and Primary Energy Requirements of the New Orleans Water Supply System

Year	Average Amount of Water Supplied (mgd)	Total Energy Consumption (MJ/day x 10^6)	Energy Required per Unit of Water Supplied* (MG/mil gal)
1973	124	1.47	11,854
1974	122	1.59	13,032
1975	123	1.53	12,439
1976	123	1.55	12,601

*Average = 12,482

The future energy requirement per unit of water supplied was obtained by averaging the figures for 1973 through 1976. This estimate was based on two assumptions:

1. The energy requirement is likely to remain approximately the same since New Orleans plans to maintain its present water supply system and not develop any new sources.
2. The present energy requirement will not be affected by new drinking water standards.

The per capita consumption data (gal/person/day) for 1973 through 1976 were extrapolated by linear regression, which indicates a small decline in the future. (City water officials also project that the per capita consumption rate will be lower in the future because it has been declining for several years.) Projected population figures (supplied by the New Orleans Chamber of Commerce) were applied to the projected per capita consumption rates to obtain a future water demand (see Table 12). The total annual energy consumption for future years was determined by multiplying the projected mgd times 365 days times the average energy requirement for 1973 through 1976. These results are presented in Table 13 and illustrated in Figure 5.

These projections indicate a 14 percent decrease in total annual energy consumption between the years 1975 and 2000. This decline is based on a decrease in the city's population.

Table 12

Projected Water Demand of the New Orleans Water Supply System

Year	Projected Per Capita Consumption (gallons/person-day)	Projected Population	Projected Water Demand (mgd)
1980	220.8	548,911	121
1990	216.8	529,939	115
2000	212.8	500,000*	106

*Estimated figure--data not available

Table 13

Projected Primary Energy Requirements of the New Orleans Water Supply System

Year	Projected Water Demand (mgd)	Projected Energy Requirement Per Unit of Water Supplied (MJ/mil gal)	Projected Total Annual Energy Consumption (MJ/Year x 10^8)
1980	121	12,482	5.51
1990	115	12,482	5.24
2000	106	12,482	4.83

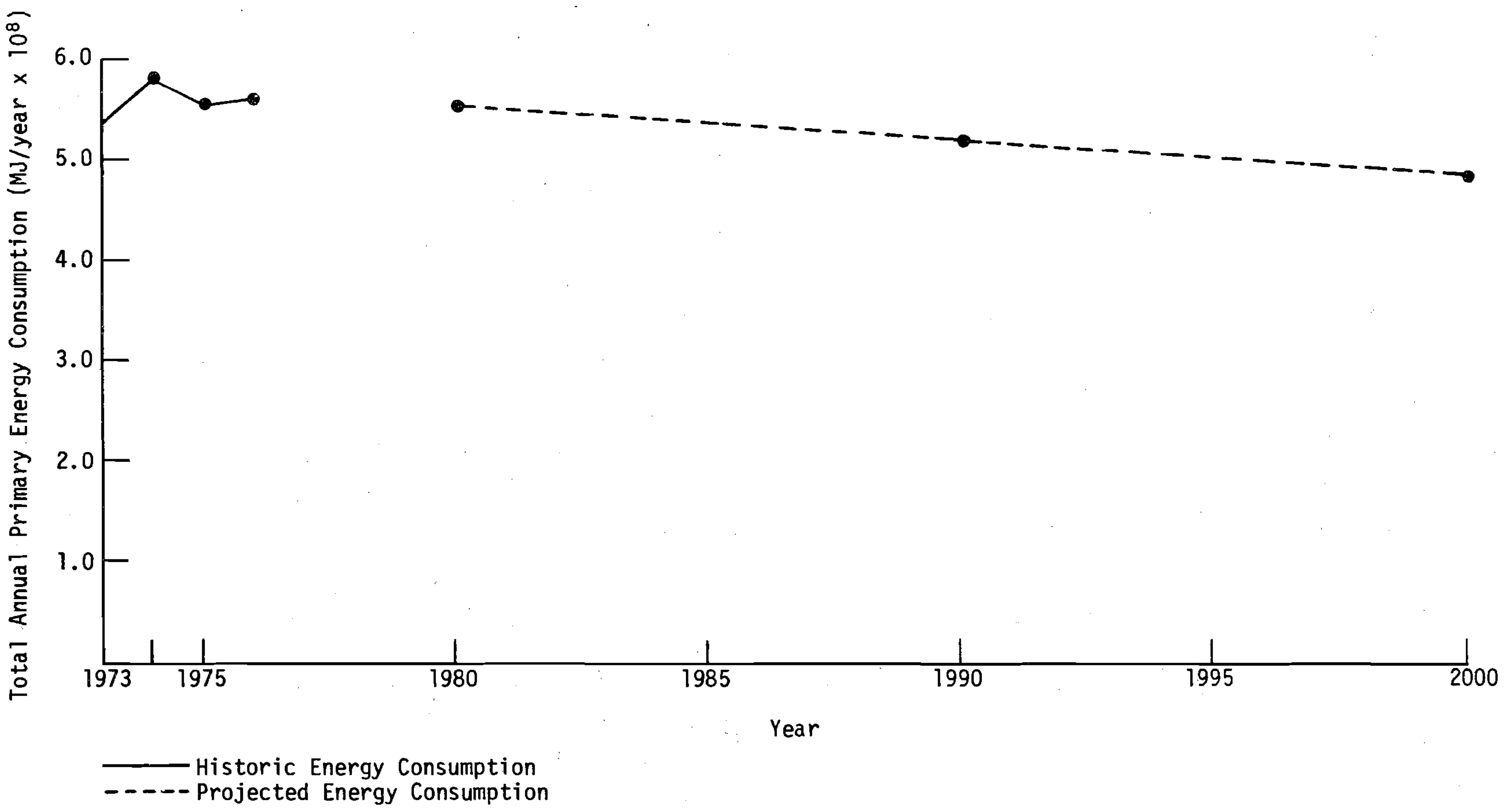


Figure 5. Historic and projected total annual primary energy consumption for the New Orleans water supply system.

As mentioned in the beginning of this section, one of our objectives in characterizing the New Orleans water supply system was to compare its energy requirements with those of Chicago's system. This comparison is presented in Table 14. The energy requirement per unit of water supplied for the years 1973 through 1976 for the two systems is shown.

Table 14

Comparison of the Primary Energy Requirement per Unit of Water Supplied for New Orleans and Chicago

Year	Energy Required per Unit of Water Supplied in New Orleans (MJ/mil gal)	Energy Required per Unit of Water Supplied in Chicago (MJ/mil gal)
1973	11,854	10,384
1974	13,032	10,321
1975	12,439	10,725
1976	12,601	10,557

Although the energy data available for New Orleans were limited, the comparison does indicate that more energy is required to supply a unit of water in New Orleans than in Chicago. This difference in the amount of energy required could be accounted for by a number of factors, e.g., the water quality of the source of water, efficiency of scale (Chicago treats roughly ten times more water daily than New Orleans, making it a more efficient system), and operational differences. To determine the importance of each of these factors, a more detailed comparison of the two systems would be necessary. To construct a flow diagram for the New Orleans system similar to the one constructed for Chicago, additional data would need to be collected. (Chicago's flow diagram is presented later in this paper.) A flow diagram for energy and materials would offer a comparison of the two systems unit by unit, which would be the best method of determining the cause of the energy requirement difference.

Denver

The water supply for the city of Denver is obtained entirely from surface sources. The water system is comprised of three divisions: the South Platte Watershed and two trans-mountain diversion systems, the Moffat System, and the

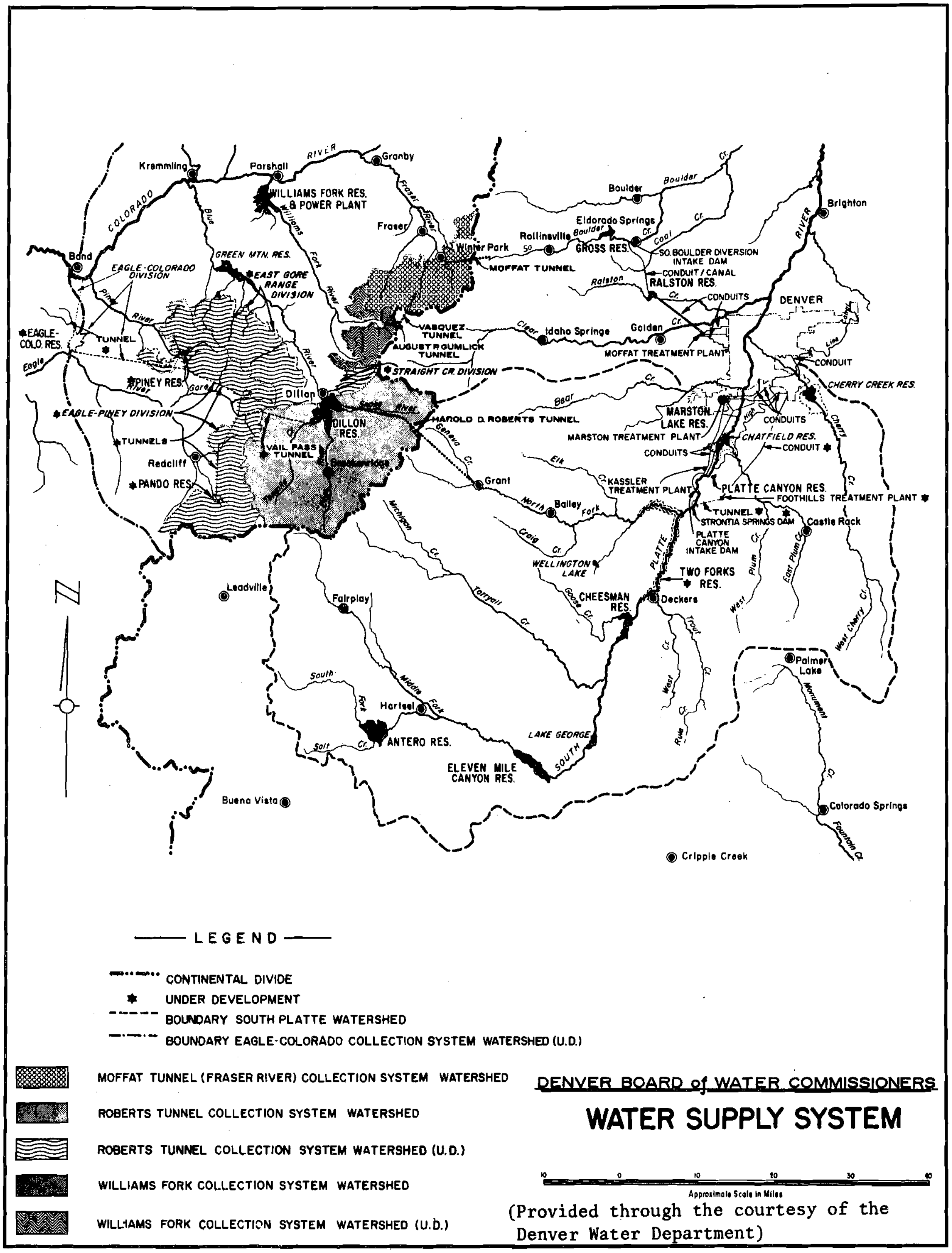
Roberts Tunnel System, the latter two diverting water from the Colorado River Basin. Of the total amount of water supplied, 43 percent is derived from the South Platte Watershed, 29 percent from the Moffat System, and 28 percent from the Roberts Tunnel System.

The city of Denver developed along the South Platte River and originally drew all of its water supply from the river. Over time, four major reservoirs, the Marston, Cheesman, Antero, and Eleven Mile Canyon Reservoirs, were constructed to increase the storage capacity of the watershed. This source eventually became inadequate to meet demands, and two trans-mountain diversion projects were built to the west of Denver to draw water from the Colorado River Basin. Construction of the first project, the Moffat Tunnel System, began in 1936. This system consists of two diversions, the Fraser River Diversion and the Williams Fork Diversion, plus a 6-mi tunnel under the Continental Divide that brings water to two storage reservoirs located northwest of Denver.

The Roberts Tunnel System, the second diversion project, was completed in 1963. This system consists of the Dillon Reservoir (which has a storage capacity of 254,036 acre ft of water) and a 23-mi tunnel under the Continental Divide. Water from this diversion discharges into the South Platte Watershed.

Denver presently operates three water treatment facilities. The Kassler plant, which has a rated capacity of 50 mgd, and the Marston plant, which has a rated capacity of 260 mgd, both treat water obtained from the Roberts Tunnel System and the South Platte Watershed. The Kassler facility employs a treatment series of presettling, slow-sand filtration, and postchlorination, while the Marston facility utilizes a series of presettling, prechlorination, coagulation, mix media filtration, and postchlorination. The Moffat treatment plant treats the water derived from the Moffat Tunnel System. This system employs presettling, coagulation, rapid sand filtration, postchlorination, and fluoridation.

The total water supply system for Denver encompasses six storage reservoirs, four operating reservoirs, and three water-treatment facilities (see Figure 6). The capacity of the operating reservoirs is 10,027.0 mil gal.



(Provided through the courtesy of the Denver Water Department)

Figure 6. Denver water supply system.

This capacity, coupled with the capacity of the storage reservoirs, gives a total water storage capacity of 169,850.4 mil gal.

The energy consumed in acquiring, treating, and distributing the water is supplied by purchased electrical power. Denver's water-supply system does include a power plant located at the Williams Fork Dam and Reservoir. The energy produced at this generating plant is not, however, used to meet the water system's energy requirements. Instead, it is delivered to the U.S. Bureau of Reclamation in return for the right to divert water at this site. In 1976, the power plant produced a total of 6,663,000 kwh. A small portion was used for local operations and the rest delivered to the U.S. Bureau of Reclamation.

The city of Denver has experienced a steady increase in population in the past decade. Projections indicate that this trend is expected to continue in the future. (See population projections in Table 15). The Denver Water Department estimates that the number of people its system will supply will increase from the 904,000 people served in 1976 to approximately 1,434,100 people in the year 2000, a 58.6 percent increase. The water department also projects that its present sources of supply will be inadequate to meet the city's water demand by 1990.

Table 15

Projected Population to Be Served by the Denver Water Supply System

Year	Population
1980	958,400
1990	1,057,200
2000	1,434,100

To avoid a water shortage in future years, Denver has made plans for additional water acquisition projects. These plans include two new transmountain diversion projects (the East Gore and the Eagle Piney projects), a dam and reservoir to increase storage in the South Platte River Basin, and a new water treatment facility. The proposed treatment plant would produce its own power with hydroturbine generators. The Denver Water Department also plans to have in operation by 1980 a 1 mgd facility that would produce potable water from sewage effluent. Water from the facility would be tested over a number of years in order to determine the feasibility of water reuse as a future source of supply.

Construction of these projects, however, has been delayed by land management controversies and environmentalists' concerns. In 1976, an Eagles Nest Wilderness Region was established in the area where Denver planned to construct its two new diversion projects. Since diversion structures are banned in such wilderness areas, the water would have to be diverted at lower elevations outside the region's boundaries, which would require the Denver Water Department to pump the diverted water to the Dillon Reservoir for storage instead of utilizing gravity flow as originally planned. The additional pumping would require an estimated 231 million kwh annually, at a cost of $2.9 million, an expenditure Denver seeks to avoid.

The construction of the proposed dam, reservoir, and water treatment facility has also been halted because of objections from environmentalists who feel an increased water supply would only contribute to Denver's growth and thus indirectly worsen the city's already serious pollution problems.

At this point, it is unclear whether Denver's controversial plans for expanding the city's water supply will be implemented. However, for the purposes of this study, it is assumed that the proposed treatment facility, storage reservoir, and diversion projects (either with additional pumping or without it) will be constructed.

The projections of the future energy requirements of Denver's water supply system presented in this study were based on historic water and energy consumption figures. Data specifying the amount of water supplied and the energy consumed in 1950 and in the years 1965 through 1976 were supplied to us by the Denver Water Department and are presented in Tables 16 and 17. The energy data presented in Table 17 is in terms of primary energy requirements. In 1976, for example, the Denver water supply system consumed 50,500,045 kwh of electricity, which gives a primary energy requirement of 8,202 MJ/mil gal. The direct energy requirement, however, is only 2,658 MJ/mil gal, which is approximately 68 percent lower than the primary energy calculation.

Table 16

Historic Water Demand of the Denver Water Supply System

Year	Average Amount of Water Supplied (mgd)	Population Served	Per Capita Consumption (gallons/person/day)
1950	100.1	490,000	204.0
1965	122.5	705,000	173.8
1966	147.7	720,000	205.1
1967	121.1	699,000	173.2
1968	148.1	710,000	208.6
1969	151.1	756,000	199.9
1970	163.2	768,000	212.5
1971	169.3	792,000	213.8
1972	175.6	812,000	216.3
1973	175.7	833,000	210.9
1974	196.2	897,000	223.2
1975	185.7	891,000	208.4
1976	187.4	904,000	207.3

Table 17

Historic Primary Energy Requirement per Unit of Water Supplied for the Denver Water Supply System

Year	Average Amount of Water Supplied (mgd)	Average Amount of Energy Consumed (mgd x 10^5)	Energy Required of Unit of Water Supplied
1950	100.1	2.94	2,940
1965	122.5	4.87	3,976
1966	147.7	6.63	4,489
1967	121.1	5.47	4,517
1968	148.1	6.66	4,497
1969	151.1	6.66	4,408
1970	163.2	7.71	4,724
1971	169.3	8.57	5,062
1972	175.6	9.65	5,495
1973	175.7	10.20	5,805
1974	196.2	15.59	7,946
1975	185.7	14.58	7,851
1976	187.4	15.37	8,202

Denver's future water demand was estimated by extrapolating linearly the per capita consumption rates for 1950 and 1965 through 1976 shown in the last column of Table 16. The projected per capita consumption rate was multiplied by the projected population to be served to determine an average daily water demand. These projections are presented in Table 18.

Table 18

Projected Water Demand of the Denver Water Supply System

Year	Projected Population to be served	Projected per Capita Consumption (gal/person/day)	Projected Water Demand
1980	958,400	217.22	208.2
1990	1,057,200	225.02	237.9
2000	1,434,100	232.82	333.9

The Denver water department predicts that the present water supply system will reach its capacity by 1990. Given this prediction, the projected water demand for 1990 (237.9 mgd) is assumed here to be equal to the capacity of the present system. The water supplied over this level of capacity must come from water added to the system by the new diversion projects. For example, the projected water demand for the year 2000 is 333.9 mgd, a 96 mgd increase over the 1990 projection. This additional 96 mgd will be drawn from the water provided by new projects.

As the data in Table 17 demonstrate, the energy required to supply a unit of water has been increasing. This increase is attributable to the fact that the additional water needed to meet the rising water demand of the city must be obtained from the more energy-intensive parts of the system. Thus, the energy requirement per unit of water supplied is likely to continue to increase in the future.

To estimate what the actual future energy requirement will be, the data in the last column of Table 17 were extrapolated using a linear regression. The results of this extrapolation were then used to develop two scenarios. Scenario 1 represents the minimum projected energy requirement, which would occur if Denver is allowed to utilize gravity flow in its two additional transmountain diversion projects, as in its original plans. In this case, the estimated future energy requirements per unit of water supplied would be the projections obtained from the linear extrapolation of the present system's energy requirements.

Scenario 2 represents the maximum projected energy requirement, which would occur if Denver is required to use pumping in its proposed diversion projects. The amount of additional energy required for pumping is estimated to be 231 million kwh, i.e., the energy requirement to add 170,000 acre ft to the system. Conversion to metric units gives 2.5664×10^9 MJ to pump 5.5395×10^{10} gal or 49,329 MJ/mil gal. (The energy requirement per unit of water supplied for this portion of the system is only a rough estimate based on available data and should be considered an upper limit. It is not known exactly how much of the 170,000 acre ft of water added to the system will actually be consumed each year or the time period over which the 170,000 acre ft of water will be added to the system.)

The projected energy requirement per unit of water supplied for Scenario 2 was calculated by employing a weighted average of the estimated future energy requirement of the present system and the estimated energy required for the portion of the system requiring additional pumping. The projections for Scenarios 1 and 2 are presented in Table 19 and illustrated in Figure 7. (The energy requirement is the same for Scenarios 1 and 2 until 1990, when the capacity of the present system will be reached. After 1990, the energy requirement for Scenario 2 will be higher than Scenario 1 to account for the additional energy required to pump water.)

Table 19

Projected Primary Energy Requirement per Unit of Water Supplied for Scenarios 1 and 2 for the Denver Water Supply System

Year	Projected Energy Requirement per Unit of Water Supplied Present System (MJ/mil gal)	Scenario 1 (MJ/mil gal)	Scenario 2 (MJ/mil gal)
1980	7,626.7	7,626.7	7,626.7
1990	9,611.7	9,611.7	9,611.7
2000	11,596.7	11,596.7	21,583.2

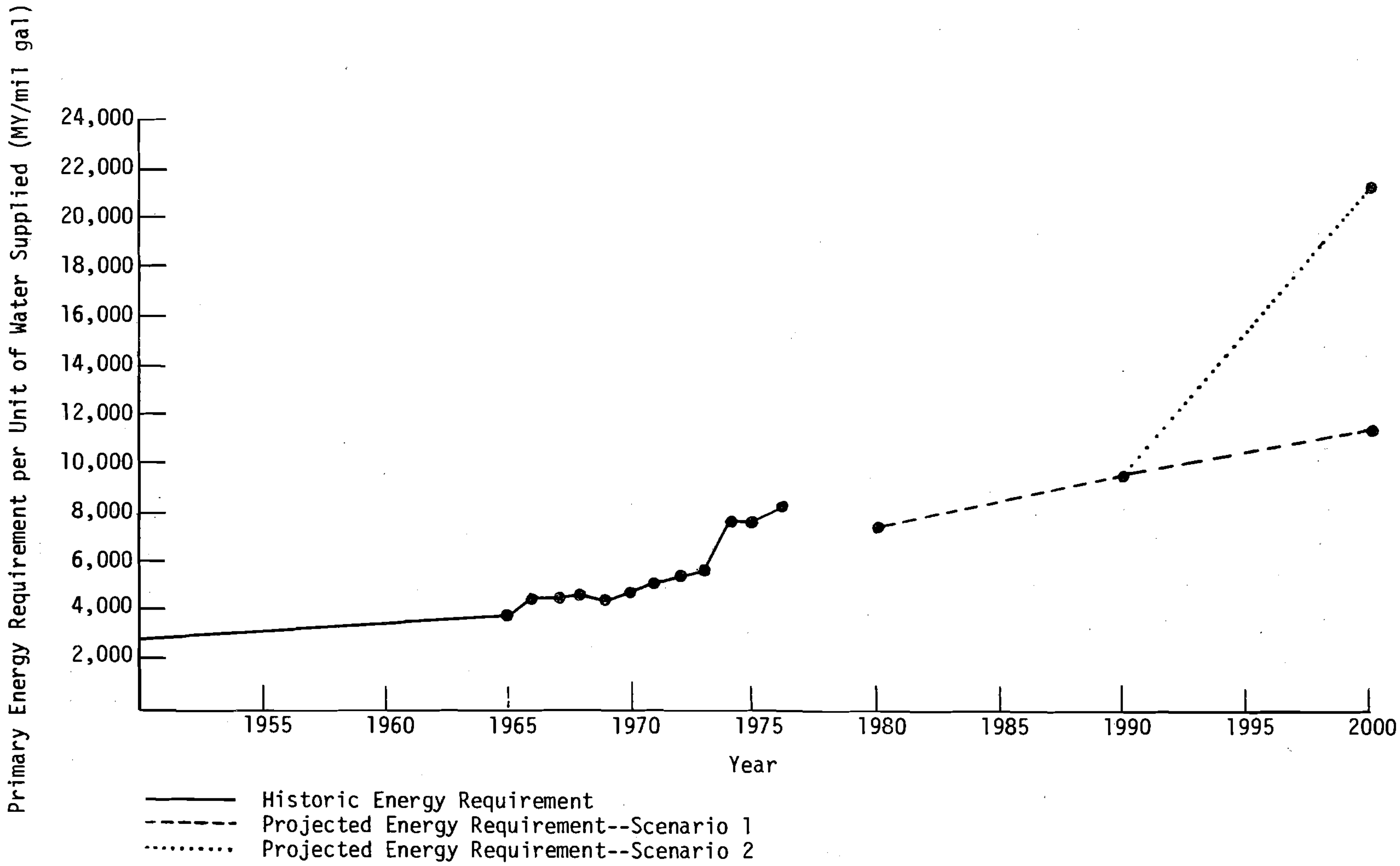


Figure 7. Historic and projected primary energy requirement per unit of water supplied for the Denver water supply system.

The future total annual energy consumption was calculated by multiplying the projected average daily demand of water times 365 days times the projected energy requirement per unit of water supplied for Scenarios 1 and 2. These results are tabulated in Table 20 and illustrated in Figure 8.

Table 20

Projected Total Annual Primary Energy Consumption for Scenarios 1 and 2 for the Denver Water Supply System

Year	Projected Total Annual Energy Consumption Scenario 1 (MJ/year x 10^8)	Scenario 2 (MJ/year x 10^8)
1980	5.80	5.80
1990	8.35	8.35
2000	14.13	26.30

Comparison between the years 1975 and 2000 for both Scenarios 1 and 2 indicates there will be a very significant increase in both the energy required per unit of water supplied and the total annual energy consumption. For Scenario 1, the percent increase between 1975 and 2000 for the energy requirement is 47.7 percent, and for the total amount of energy consumed annually the increase is 165.6 percent. For Scenario 2, the increase is 174.9 percent for the energy requirement and 394.4 percent for the total annual amount of energy consumed. Combining the two scenarios gives a range of 47.7 to 174.9 percent increase for the energy requirement and a 165.6 to 394.4 percent increase for the total annual energy consumption.

It should be emphasized that these percent increases are only rough estimates based on available data and are presented as upper limits for both scenarios. In Scenario 1, for example, the projections for the energy required per unit of water supplied for the present system were based on the assumption that this energy requirement will continue to increase at the same rate as in the past. Although all indications are that this energy requirement will continue to rise, it may not increase as rapidly as in the past and may actually level off before the year 2000. The increase in this energy requirement will also be affected by the fact that the proposed treatment

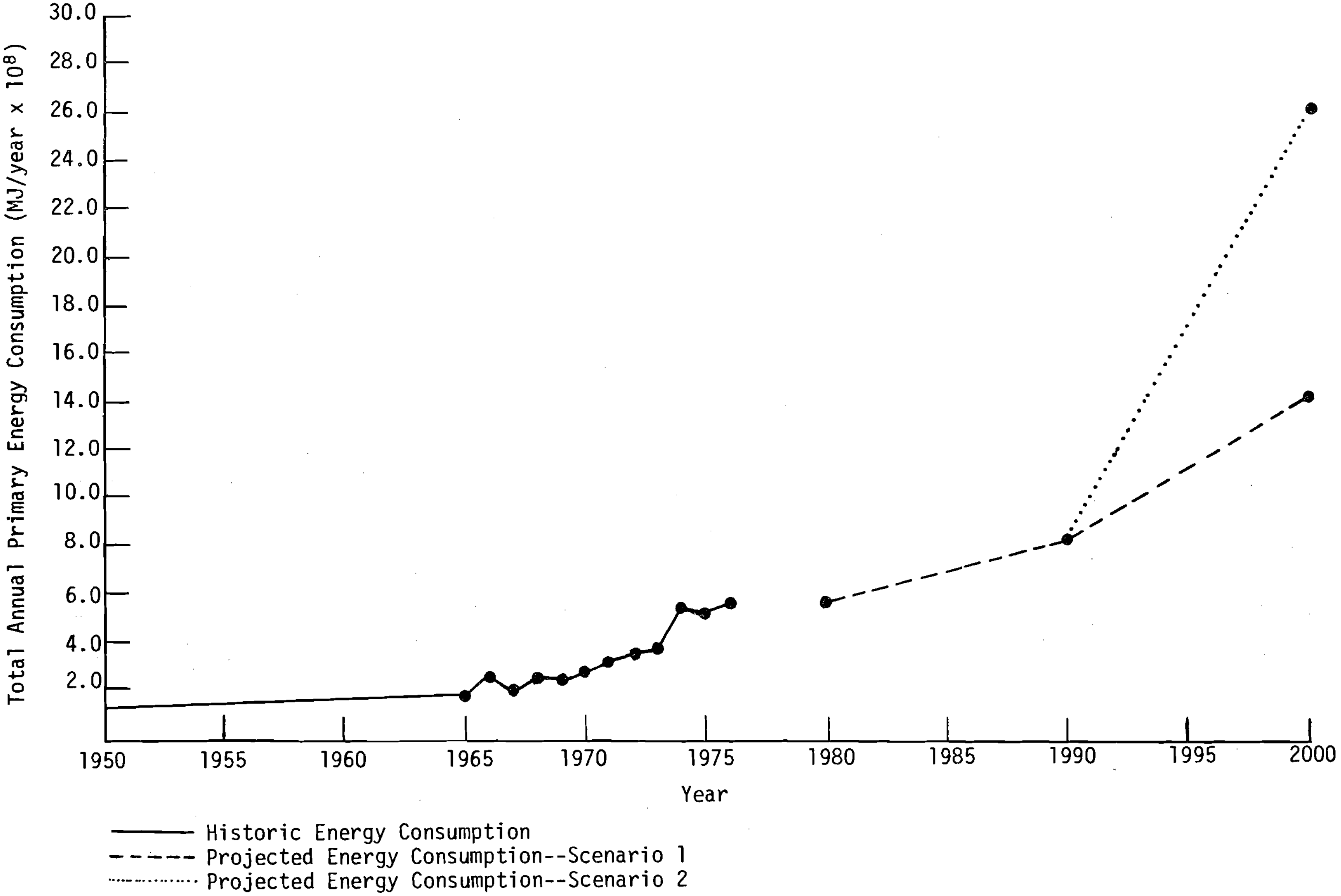


Figure 8. Historic and projected total annual primary energy consumption of the Denver water supply system.

facility will produce its own power on site to operate its treatment series. In Scenario 2, the very large increase in both the energy requirement and total annual energy consumption is also presented as an upper bound. The large increase in energy consumption due to the required pumping for the two new diversion projects will most likely be distributed over more than the ten years between 1990 and 2000.

One observation that can be drawn from this preliminary study of the Denver water supply system is that the difference in energy consumption if Denver is required to pump in its new diversion projects will be quite significant. The situation should be carefully analyzed so that a solution can be reached that would best balance the energy and environmental concerns involved.

Although these energy consumption projections may be high, the fact remains that Denver will need to contend with a rapidly growing population and accompanying rise in water demand at the same time the energy required to supply a unit of water will be increasing. Of the cities examined in this study, Denver faces the most criticial water-energy situation.

San Antonio

One hundred percent of San Antonio's water supply is from groundwater, making it one of the largest cities in the country to depend entirely on groundwater as the source of water. The source of San Antonio's groundwater is the Edwards Aquifer, a limestone formation extending approximately 175 mi through six counties. San Antonio is one of many users in the area drawing from this aquifer.

The water level of San Antonio's wells exceeds 620 ft below the surface, but the water that is pumped out is under artesian pressure, which helps to reduce the amount of energy required to pump it to the surface. The water is of adequate quality so that it only requires chlorination. Thus, at present, the city does not maintain any water treatment facilities. The energy needed to supply water is the energy consumed in well pumping and in the distribution of the water through the city.

Data specifying the depth to groundwater for San Antonio's wells indicate that the water levels have remained relatively constant over time (see Figure 9). Presently, the aquifer is not being mined, i.e., withdrawals do not exceed recharge. However, the withdrawal rates are reaching a critical point so that, if they continue to increase, users will begin mining the aquifer in the near future.

San Antonio has experienced a steady increase in population, which is expected to continue in the future. An increase in the water demand has accompanied this growth in population. If mining of the Edwards Aquifer is to be prevented, San Antonio will need to augment its present supply with a new source by 1990.

Plans for supplying water to the city in the future include the addition of two reservoirs: the Canyon Reservoir, which presently exists and is located north of the city, and the Applewhite Reservoir, a proposed reservoir to be constructed south of San Antonio. San Antonio would continue to draw from the aquifer but would add 1,629.3 mil gal/year from the Applewhite Reservoir by 1990, and 18,051.8 mil gal/year from the Applewhite and Canyon Reservoirs by the year 2000. This additional surface water would need to be treated, requiring San Antonio to build a water treatment facility. The water would be transported to the treatment plant by pipe, treated, and then distributed through the city. The distance from the proposed Applewhite Reservoir to the new treatment facility would be approximately 0.8 mi and 26.8 mi from the existing Canyon Reservoir.

The city water board of San Antonio provided us with the total amount of energy consumed by their water supply system in the years 1960, 1965, and 1970 through 1976, along with the average amount of water supplied during that period (see Table 21). The energy data presented in Table 21 are in terms of primary energy requirements. In 1976, for example, 51,539,000 kwh of electricity were needed to operate the system. Converting this to primary energy gives an energy requirement of 15,422 MJ/mil gal. If, instead, the direct energy requirement is calculated, the requirement is 4,990 MJ/mil gal, which is approximately 68 percent lower than the primary energy calculation.

Figure 9. Depth to groundwater for the San Antonio water supply system.

Table 21

Historic Water Demand and Primary Energy Requirements for the San Antonio Water Supply System

Year	Average Amount of Water Supplied (mgd)	Total Energy Consumption (MJ/day x 10^6)	Energy Requirement per Unit of Water Supplied (MJ/mil gal)
1960	73.6	1.11	15,081
1965	78.7	1.15	14,612
1970	94.9	1.41	14,857
1971	111.6	1.73	15.501
1972	108.2	1.55	14,325
1973	100.5	1.38	13,731
1974	104.8	1.65	15,744
1975	100.2	1.55	15,469
1976	101.8	1.57	15,422

In regard to the future supplementation of the city's present water source, the city water board has made estimates as to the amount of additional energy that will be needed to transport, treat, and distribute the reservoir water. These estimates are presented in Table 22.

To calculate the future energy requirement per unit of water supplied, it was assumed that San Antonio would avoid mining the Edwards Aquifer by increasing its supply with the proposed reservoir system. It was also assumed that the aquifer would not be mined by other users in the area so that the existing water level of San Antonio's wells would not decrease drastically. The present energy requirement (energy consumed in pumping and distributing) was extrapolated to determine the future energy requirement of acquiring groundwater. The energy required to transport, treat, and distribute the additional reservoir water was then considered. A weighted average (mil gal x energy requirement) was employed to determine the future energy requirement per unit of water supplied. The results are shown in Table 23. The historic and projected energy requirements are illustrated in Figure 10.

To obtain an estimate of the amount of water that will be supplied in 1980, 1990, and 2000, the historic per capita consumption rates for San

Table 22

Future Primary Energy Requirements for Supplemental Surface Water Supply for the San Antonio Water Supply System

Year	Annual Amount of Water to Be Added from Reservoirs (mil gal/Year)	Energy Required to Transport Reservoir Water to Treatment Facility (MJ/mil gal)	Energy Required to Treat Water at Treatment Plant (MJ/mil gal)	Energy Required to Distribute Additional Water Through City (MJ/mil gal)	Total Energy Required to Transport, Treat, and Distribute Reservoir Water (MJ/mil gal)
1990	1,629.3	18,922	2,728	12,956	34,606
2000	18,051.8	5,127	1,200	14,555	20,882

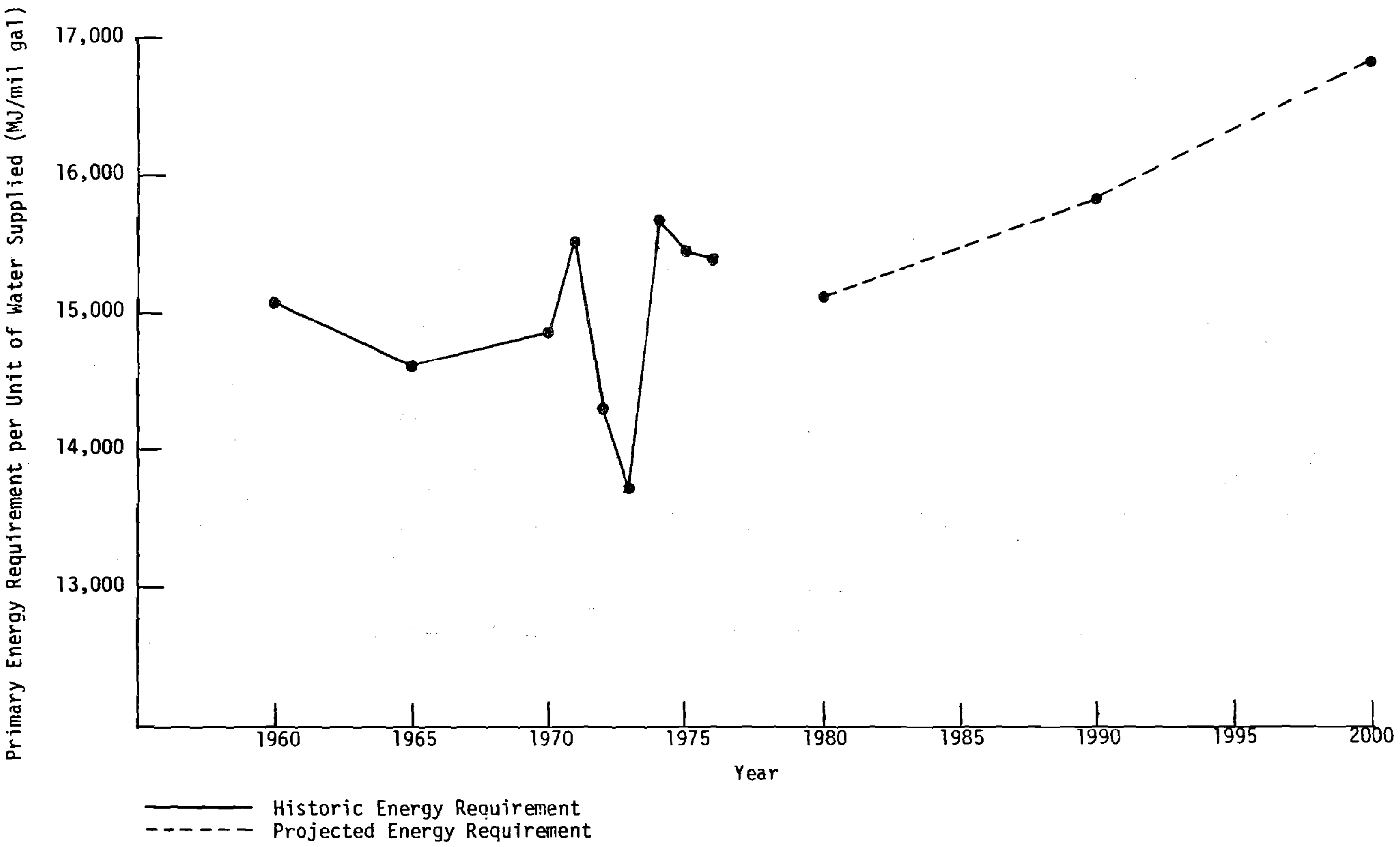


Figure 10. Historic and projected primary energy requirement per unit of water supplied for the San Antonio water supply system.

Table 23

Projected Primary Energy Requirement per Unit of Water Supplied for the San Antonio Water Supply System

Year	Energy Required to Supply Groundwater (MJ/mil gal)	Energy Required to Transport, Treat, and Distribute Reservoir Water (MJ/mil gal)	Total Energy Required per Unit of Water Supplied (MJ/mil gal)
1980	15,166	0	15,166
1990	15,378	34,606	15,841
2000	15,590	20,882	16,843

Antonio were extrapolated using a linear regression. The projected per capita consumption rates were applied to projected population figures to obtain the future average water demand. Table 24 shows these projections. Because San Antonio's population is expected to increase, it is likely that the water demand will also increase.

Table 24

Future Water Demand of the San Antonio Water Supply System

Year	Projected per Capita Consumption (gal/person/day)	Projected Population	Projected Water Demand (mgd)
1980	180	740,867	124
1990	171	1,092,037	187
2000	175	1,198,319	209

The total annual amount of energy to be consumed by San Antonio's water system in the future was calculated by multiplying the estimated future energy requirement by the estimated water demand. These results are shown in Table 25 and illustrated in Figure 11. The fluctuation between the years 1990 and 2000 can be attributed to two factors. The major reason for the decline in the energy requirement per unit of water supplied is the addition of the Canyon Reservoir to the system. The water obtained from this reservoir will be transported by gravity to the new treatment facility. Much more water will be added to the system in 2000 from the Canyon Reservoir than from the

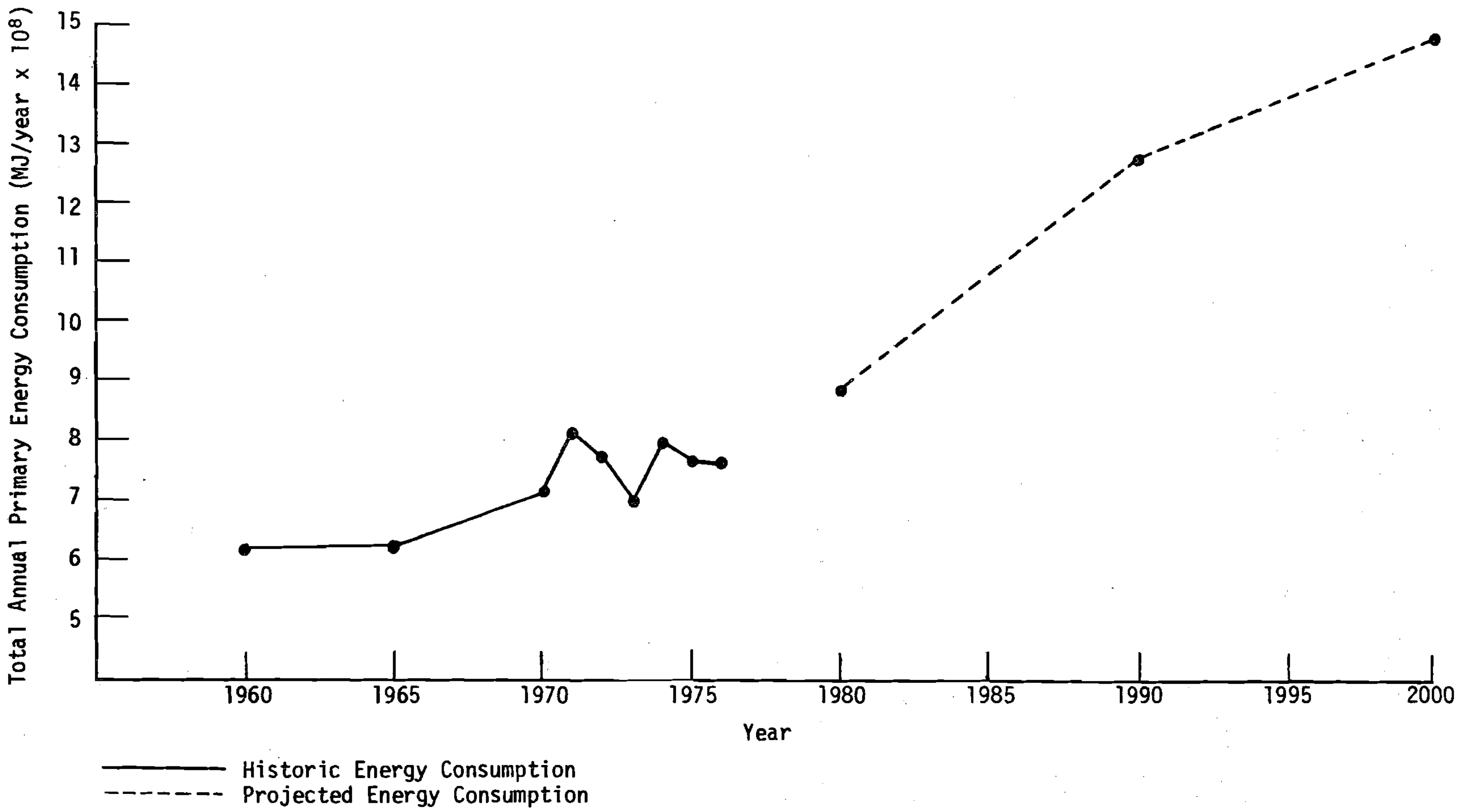


Figure 11. Historic and projected total annual primary energy consumption for the San Antonio water supply system.

Applewhite Reservoir (13,164 mil gal/year vs 4,888 mil gal/year), which would explain the decline in MJ/mil gal. The fluctuation in the energy requirement between 1990 and 2000 can also be accounted for by an increase in efficiency at the water treatment facility. More water would be treated in 2000, which would tend to decrease the energy requirement per unit of water supplied.

Table 25

Projected Primary Energy Requirements
of the San Antonio Water Supply System

Year	Projected Water Demand (mgd)	Projected Energy Requirement per Unit of Water Supplied (MJ/mil gal)	Projected Total Annual Energy Consumption (MJ/year x 10^8)
1980	124	15,166	6.86
1990	187	15,841	10.81
2000	209	16,843	12.85

Comparison of the years 1975 and 2000 indicates a 9 percent increase in the energy requirement per unit of water supplied and a 127 percent increase in the total annual amount of energy consumed. The large increase in the amount of energy consumed is attributable to the expected increase in population and accompanying water demand. Projections indicate that the population of San Antonio is expected to almost double between the years 1975 and 2000.

Los Angeles

Los Angeles draws its water from both surface- and groundwater sources. The major portion of the city's water supply (approximately 80 percent) is transported by aqueduct from the Owens Valley Watershed, located on the eastern slopes of the Sierra Nevada, northeast of Los Angeles. Groundwater comprises 14 percent of the total water supply and is pumped from the groundwater basin in the San Fernando Valley. The remaining 6 percent is purchased from the Metropolitan Water District of Southern California. This water is obtained from Northern California through the California Aqueduct and from the Colorado River through the Colorado River Aqueduct.

Los Angeles is located in an area characterized by semiarid conditions. Since this region normally receives very little rainfall each year, supplying water to support a growing population has been a serious problem in the past and continues to be a major concern today. At the turn of this century, after Los Angeles experienced a series of dry years and rapid population growth, the city was forced to develop other sources of water. It was at this time that the first phase of the Owens Valley Aqueduct was proposed and constructed. The melting snow and frequent rainfall in the mountain range northeast of Los Angeles provide a relatively abundant source of water. To transport this water into Los Angeles, a 233-mi aqueduct was completed in 1913. In 1940, this aqueduct was lengthened to 338 mi. In addition, a second aqueduct was completed in 1970.

As previously mentioned, Los Angeles also obtains water from the Metropolitan Water District of Southern California, which was established in 1928 and is comprised of a number of cities in this region. The agency was formed in order to consolidate efforts to import more water into the coastal plains of southern California. In 1941, the district constructed the Colorado River Aqueduct, and in 1973 it completed the California Aqueduct or State Water Project, another importation project. (These two aqueducts are illustrated in Figure 12.)

Los Angeles currently has the right to purchase 32 percent of the district's water, although this right can be limited in times of drought (as in the past two years). A spokesman for the water department indicated that Los Angeles expects to obtain more of its water supply from the Metropolitan Water District in the future. This additional water will be drawn from the California Aqueduct System. The city's present withdrawals from the Owens Valley, the San Fernando Valley, and the Colorado River are close to reaching legal limits. (These limits are presented in Table 26.)

The Los Angeles water supply system is unique in that it produces much more energy than is required to operate it. Energy is produced by the Owens Valley Aqueduct System. As water is brought down from the higher elevations by gravity flow, hydroelectric power is generated at a number of power plants located along the water route. This generating system is able to produce 2400 kwh/acre ft of water delivered, or 81,828.8 MJ/mil gal. The energy produced well exceeds the energy required to operate the water supply system so

Provided through the courtesy of the Los Angeles Department of Water and Power.

Figure 12. Los Angeles water supply system.

Table 26

Water Supply Sources and Withdrawal Limits of the Los Angeles Water Supply System

Source of Supply		Legally Imposed Withdrawal Limits (mil gal/year)
Groundwater from San Fernando Valley		33,237
Owens Valley Watershed		157,133
Colorado River		8,249
	Total	198,619

that much of the power generated is sold to the residents of Los Angeles and to other utilities. In 1975, for example, approximately 147,799.5 mil gal of water were supplied from the Owens Valley Watershed. This amount times the energy produced per unit of water supplied (81,828.8 MJ/mil gal) gives a total of 1.209×10^{10} MJ generated. Of this total, only 1.03×10^{9} MJ were consumed by the water supply system.

While the Owens Valley Aqueduct System produces energy, other portions of the Los Angeles water supply system consume energy. Energy is required to pump groundwater in the San Fernando Valley and to import water through the California and Colorado River Aqueducts. The California Aqueduct is the most energy intensive part of the water supply system. To pump water over the mountains in the north into the coastal plains of southern California, a large amount of energy is required. Although there are some power recovery plants located along its route, the power they generate constitutes only a small portion of the total energy required to import the water. The energy required to supply a unit of water is 3200 kw/acre ft of water, or 109,105 MJ/mil gal. The energy required to obtain water via the Colorado River Aqueduct is also significant. The energy required to supply a unit of water from this system is 1900 kw/acre ft of water, or 64,781 MJ/mil gal.

The present amount of energy required per unit of water supplied in Los Angeles is relatively low because most of the city's water is supplied from the energy-producing part of the system rather than from the energy-consuming portion. Two other factors also contribute to the low energy requirement.

Gravity flow is maximized to reduce distribution pumping through the city. Also, the water obtained from the Owens Valley Watershed is of adequate quality, so only chlorination is required.

The energy required, however, to supply a unit of water in Los Angeles is expected to increase in the future. Los Angeles is planning to build a water filtration plant by the mid-1980s to treat water supplied from the Owens Valley Watershed. The water filtration plant is being constructed for the primary purpose of removing suspended solids. The energy requirement will also increase as Los Angeles is compelled to obtain more of its water from the California Aqueduct, an energy-intensive system.

The Los Angeles Department of Water and Power provided us with water consumption and energy consumption data for the years 1966 through 1977. Estimates of the amount of energy that will be required to supply a unit of water in the future were based on this data and on the knowledge that Los Angeles plans to construct a water treatment facility by the mid-1980s as well as obtain more of its water from the energy-consuming portion of its system. Data for the extreme drought years of 1976 and 1977 were not included in making these projections. If the years 1976 and 1977 (one of the driest periods in California history) are to be considered, one would also need to include data for the year 1978, which is shaping up to be one of California's wettest years. Given the purpose of this study, it was decided that it would be best to exclude these extreme years.

The historic water demand for the city of Los Angeles is presented in Table 27. To project the future water demand, the per capita consumption rate for future years was estimated to be the same as in the year 1975. This estimate is based on a projection made by the Los Angeles Department of Water and Power that the per capita consumption rate will remain at this level until the year 2000. The 1975 figure (182 gal/person/day) was multiplied by the population projections given in Table 28 to determine the future water demand. The results of these calculations are presented in Table 29. Although the per capita consumption rate is expected to remain stable, the water demand will increase because of a rise in population.

Table 27

Historic Water Demand of the Los Angeles Water Supply System

Year	Average Amount of Water Supplied (mgd)	Population Served	Average per Capita Consumption (gal/person-day)
1966	471.5	2,772,000	170
1967	464.3	2,817,000	165
1968	492.0	2,932,000	168
1969	487.4	2,965,000	164
1970	529.3	2,975,000	178
1971	521.1	2,862,000	182
1972	538.5	2,858,000	188
1973	511.2	2,870,000	178
1974	504.3	2,836,000	178
1975	506.1	2,786,000	182*
1976	545.2	2,848,000	191
1977	505.0	2,861,000	177

*This figure was estimated to be the per capita consumption rate to the year 2000.

Table 28

Projected Population to Be Served by the Los Angeles Water Supply System

Year	Projected Population to Be Served
1980	2,837,000
1990	2,972,000
2000	3,055,000

Table 29

Projected Water Demand of the Los Angeles Water Supply System

Year	Projected per Capita Consumption (gal/person-day)	Projected Population to Be Served	Projected Water Demand (mgd)
1980	182	2,837,000	516.3
1990	182	2,972,000	540.9
2000	182	3,055,000	556.0

The historic energy consumption for Los Angeles's water supply system is presented in Table 30. The energy data listed in this table are in terms of primary energy requirements. In 1975, for example, the Los Angeles water supply system consumed 92,484,293 kwh of electricity, which gives a primary energy requirement of 5,562 MJ/mil gal. The direct energy requirement, however, is only 1,802 MJ/mil gal, which is approximately 68 percent lower than the primary energy calculation.

Table 30

Historic Primary Energy Requirement per Unit of Water Supplied for the Los Angeles Water Supply System

Year	Amount of Energy Consumed (MJ/day x 10^6)	Amount of Water Supplied (mgd)	Energy Required per Unit of Water Supplied (MJ/mil gal)
1966	3.151	471.5	6,683.4
1967	2.739	464.3	5,899.3
1968	3.256	492.0	6,618.4
1969	2.648	487.4	5,432.6
1970	2.572	529.3	4,859.7
1971	2.814	521.1	5,400.0
1972	2.529	538.5	4,696.4
1973	2.604	511.2	5,093.7
1974	2.623	504.3	5,201.3
1975	2.815	506.1	5,562.0
1976	3.460	545.2	6,346.3
1977	3.610	505.0	7,148.5

Excluding the extreme years of 1976 and 1977, when Los Angeles was forced to obtain a higher percentage of its water supply from the State Water Project (California Aqueduct), the data in Table 30 do not demonstrate a decisive upward or downward trend in the energy requirement. Therefore, to project the energy requirement in future years, the figure for 1975 (5,562 MJ/mil gal) was estimated to be the energy requirement of the present system. The projected amount of energy that will be required to treat a unit of water at the proposed treatment facility and the additional energy that will be required because of a greater reliance on the State Water Project were added to this base energy requirement.

The proposed treatment plant will be constructed by the mid-1980s and will treat the Owens Valley water, or approximately 80 percent of the total water supply. The treatment facility will employ a series of coagulation, deep-bed media filtration, and ozonation. The Los Angeles Department of Water and Power has not made a projection as to how much energy will be required to treat a unit of water. Since these data are missing, an estimate was made based on projections for the proposed San Antonio treatment facility, which will require 1,199 MJ/mil gal. The energy requirement for the proposed Los Angeles facility is estimated to be the same.

To determine how the energy requirement per unit of water supplied will be affected by a greater reliance on the State Water Project, the maximum amount of water which Los Angeles can legally withdraw from its other three sources (given in Table 26) was compared to the projected water demand for the years 1980, 1990, and 2000. This comparison indicates that between the years 1990 and 2000 Los Angeles will come to depend more heavily on the State Water Project. The difference between the projected water demand for the year 2000 and the total amount of water to which Los Angeles is limited from its other three sources is 11.8 mgd. This figure is assumed to be the approximate amount of water that will be drawn by the city from the State Water Project in the year 2000. The 11.8 mgd was then multiplied by the amount of energy required to supply a unit of water (109,105 MJ/mil gal) from this source to estimate the additional energy that will be needed.

The projected energy requirements per unit of water supplied that are presented in Table 31 were calculated in the following manner. The energy requirement for 1980 was estimated to be identical to that of 1975, since the supply system is not expected to undergo any changes in the intervening years. The projected energy requirement for 1990 was determined by adding on to the 1980 figure, an estimate of the energy that will be required to treat a unit of water at the proposed treatment facility. (The plant is planned to be in operation by the mid-1980s.) The energy requirement for the year 2000 was calculated by determining the weighted average of the energy requirement for 1990 and the energy requirement to supply water from the State Water Project. These projected energy requirements as well as historic energy requirements are graphed in Figure 13.

Table 31

Projected Primary Energy Required per Unit of Water Supplied for the Los Angeles Water Supply System

Year	Projected Energy Requirement per Unit of Water Supplied (MJ/mil gal)
1980	5,562
1990	6,761
2000	8,933

From these projected energy requirements and the estimated water demand for future years, the projected total annual energy consumption was calculated. These calculations are presented in Table 32 and illustrated in Figure 14.

Table 32

Projected Total Annual Primary Energy Consumption of the Los Angeles Water Supply System

Year	Projected Water Demand (mgd)	Projected Energy Requirement per Unit of Water Supplied (MJ/mil gal)	Projected Total Annual Consumption (MJ/year x 10^8)
1980	516.3	5,562	10.5
1990	540.9	6,761	13.3
2000	556.0	8,933	18.1

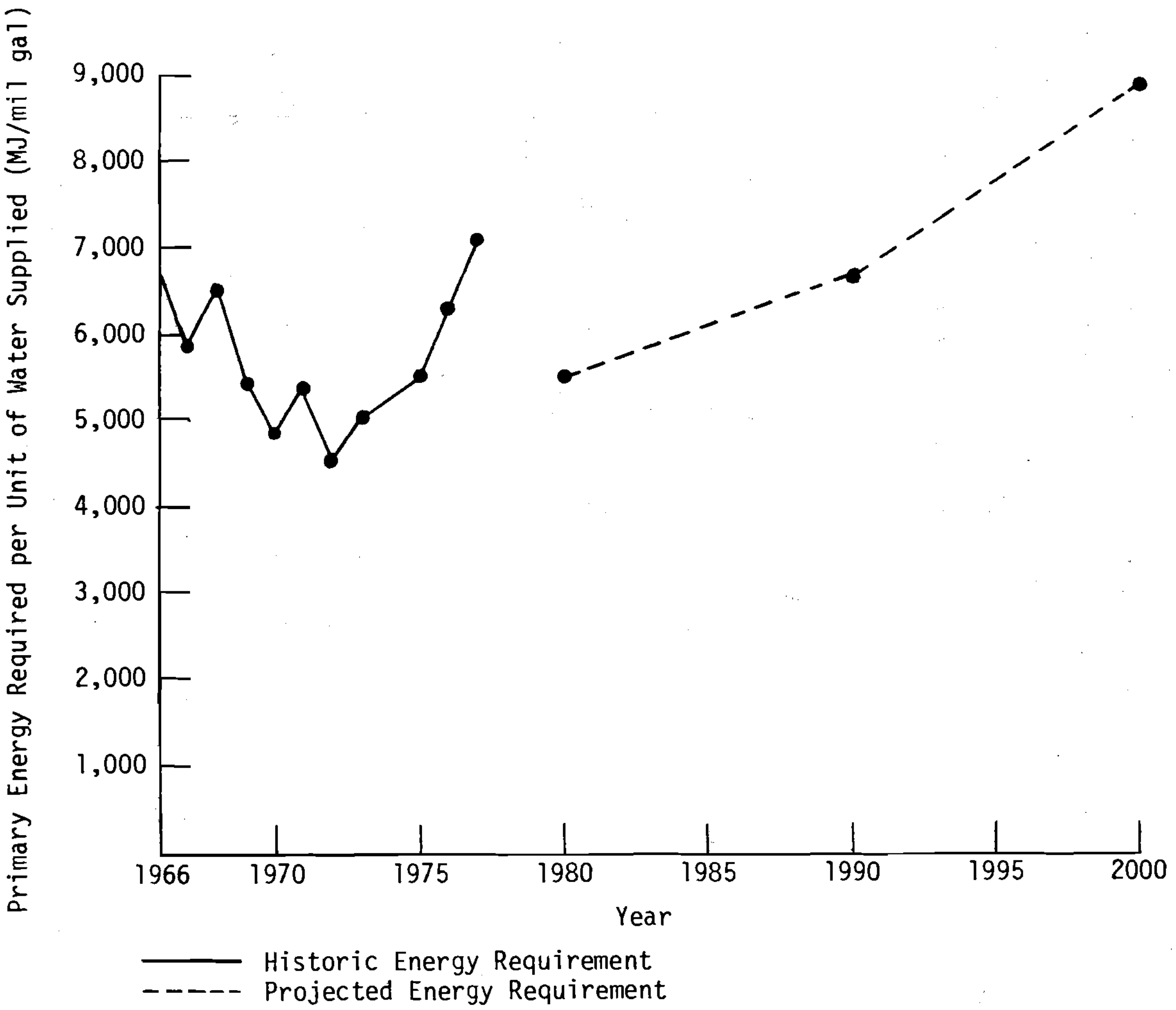


Figure 13. Historic and projected primary energy requirements to supply a unit of water for the Los Angeles water supply system.

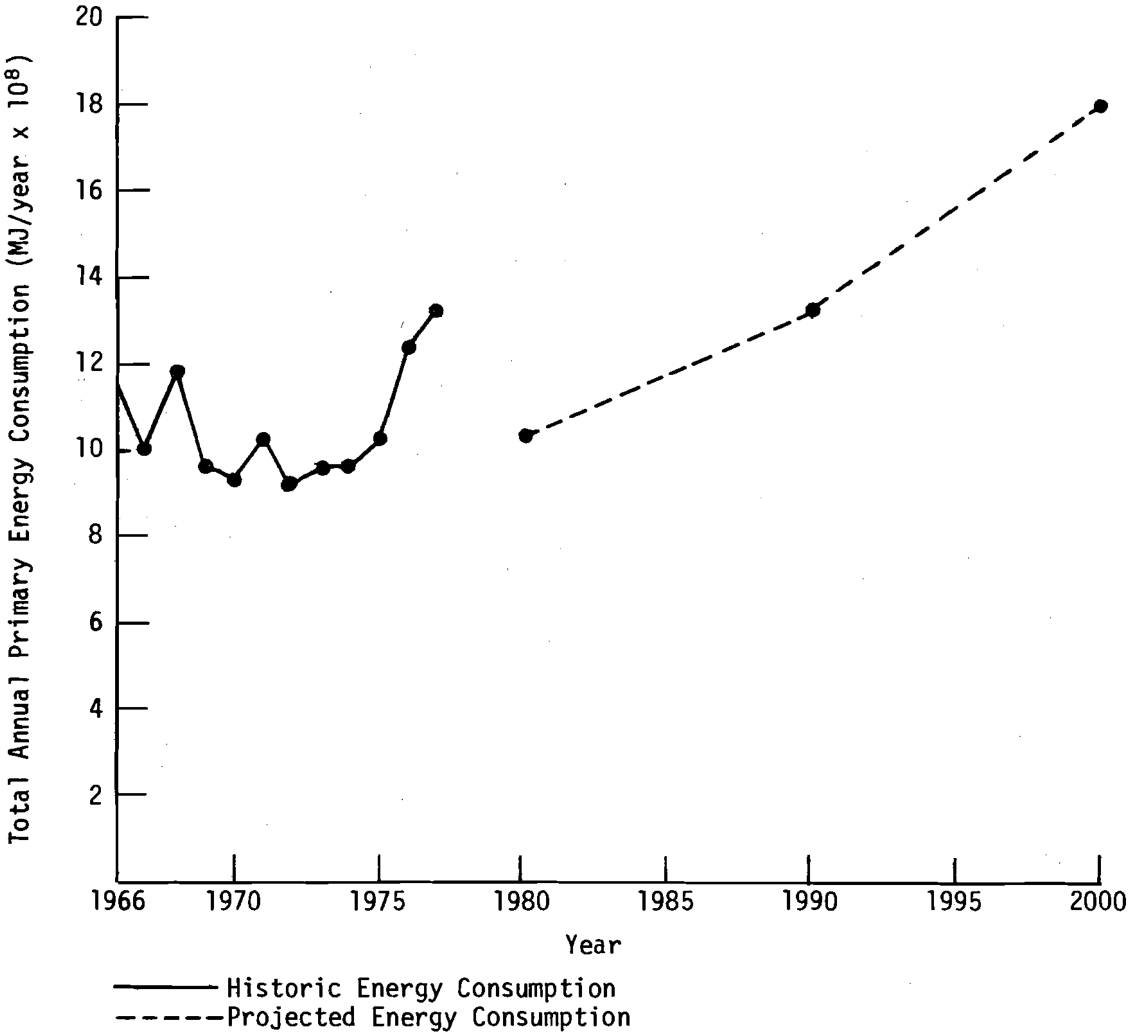


Figure 14. Historic and projected total annual primary energy consumption for the Los Angeles water supply system.

Comparison between the years 1975 and 2000 indicates that the amount of energy required per unit of water supplied by the Los Angeles system will increase by 60.6 percent and that the total annual energy consumption will increase by 75.7 percent. Although these increases are significant, the projected amount of energy that will be consumed by Los Angeles's water supply system will still be well under the amount of energy that the system will be able to produce. For example, the maximum amount of water that can be legally withdrawn from the Owens Valley Watershed (given in Table 26) is 157,133 mil gal/year. This figure, times the energy produced by each unit of water delivered (81,828.8 MJ/mil gal), gives a maximum amount of 1.286×10^{10} MJ/year.

From the results of this pilot study, it can be concluded that Los Angeles will not be faced with a water-energy problem in the future. The city's water supply system is unique in that it will produce much more energy than will be required to operate it.

Summary

As originally stated in the introduction to this chapter, the objective of this part of the study was to determine how much energy is presently required to supply water and whether or not this energy requirement will increase significantly by the year 2000. By focusing on the energy requirements of these six major cities, we hoped to determine, in a general sense, whether or not the energy needed to supply water will constitute a significant portion of our total national energy budtet in future years.

Table 33 summarizes the energy projections for the six cities studied. The last column of the table lists the projected percentage changes in the total annual energy consumption between the years 1975 and 2000. As these figures indicate, the amount of energy that will be required to supply water is actually projected to decrease in two of the cities (St. Louis and New Orleans) while it is projected to increase by different degrees in the other four cities.

While the amount of energy required to supply water in New Orleans and St. Louis in the future will not, apparently be a major concern, energy requirements may become a much more important factor in the other four cities,

Table 33

Projected Changes in the Energy Required to Supply a Unit of Water and Total Annual Energy Consumption

City	Projected Change in the Energy Required to Supply a Unit of Water (percent)		Projected Change in the Total Annual Energy Consumption (percent)	
St. Louis	----		32	(-)
New Orleans	----		14	(-)
Chicago	5.1 - 7.7	(+)	25.8 - 36.5	(+)
Los Angeles	60.6	(+)	75.7	(+)
San Antonio	9.0	(+)	127.0	(+)
Denver	47.7 - 174.9	(+)	165.6 - 394.4	(+)

(-) denotes decrease
(+) denotes increase

where the amount of energy needed to supply water is expected to increase. To determine their significance, the percentage increases presented in the last column of Table 33 were compared to projected increases in domestic energy consumption for the nation as a whole. These projections were made by the Federal Energy Administration (which is now the Department of Energy) and are based on two scenarios; one scenario includes conservation practices and the other does not. The two scenarios give a range of increase in domestic energy consumption of 49 to 75 percent between the years 1975 and 2000.

Comparison of the percentage increases in Table 33 and the projected range of increase in domestic energy consumption given by the FEA indicates that three of the cities in this study (Los Angeles, San Antonio, and Denver) will have a higher rate of increase in their water supply energy requirements than the national rate of increase of total energy consumption. One city (Chicago) has a lower rate.

In all of the four cities in which the amount of energy consumed in supplying water is expected to increase, it is important to place this increase in the context of the city's total power consumption. In Los Angeles, for example, where the water supply system produces much more energy than it consumes, and where the projected increase in the amount of energy needed to supply water is relatively modest compared to a city like Denver, it would be an oversimplification to conclude that the amount of energy needed to supply water will not be a concern. Los Angeles has come to rely on the excess power produced by its water supply system, but the amount of power that can be generated is limited by the amount of water that can be legally withdrawn from the Owens Valley Watershed. Therefore, the additional energy that will be needed to operate the water supply system in the future will diminish the amount of relatively cheap power available to the city. This situation becomes more relevant in light of the expected increases in population in Los Angeles, Denver, and San Antonio.

It should be pointed out that if we were to look at water supply systems beyond the year 2000, it is likely that more energy-intensive water supply systems would be in operation. This projection is particularly true in the arid Southwest and West Coast, where desalination, interbasin transfer, and water reuse projects are likely to become more widespread. Denver, for example, is beginning to experiment with water reuse projects to determine their feasibility as future sources of water. Los Angeles is already involved in an interbasin transfer project although this project only supplies a small portion of its total water demand. The city plans, however, to draw more of its water from this source in the future. (Although Los Angeles does derive some of its water from an interbasin transfer project, it obtains the majority of its water supply from its own private aqueduct system. Other communities in this area must rely more heavily on interbasin transfer projects, so energy is a bigger factor in supplying water in southern California than the Los Angeles system indicates.)

The results in Table 33 do not reveal any uniform change in the amount of energy that will be required to supply water in the six cities studied. Based on these results, therefore, it is difficult to project the magnitude of change in the amount of energy required to supply water in the nation as a whole. These results do, however, emphasize that there will be large regional differences in the amount of energy required to supply water. While the three cities in the Midwest are not expected to experience significant increases in their energy requirements to supply water, the three western cities are, which seems to suggest that the amount of energy that will be needed to supply water in the future will be more a regional problem than a national concern.

The results presented in this study demonstrate that one of the most important factors affecting the energy requirement to supply water is the shift of population. The projected decrease in the amount of energy that will be required to supply water in St. Louis and New Orleans is directly attributable to a decline in population. Denver, Los Angeles, and San Antonio, on the other hand, are experiencing large increases in population. The increase in water demand accompanying this rise in population has already begun to put a strain on the limited available sources of water in these cities. As more energy-intensive water supply systems are required to support growing populations, water and the energy needed to supply it may well become a limiting factor in the further growth of these cities and the regions they represent.

While there is an ample supply of water in the midwestern and eastern sections of the country, water quality has become a major concern. The energy projections in this study were based on the assumption that drinking water standards will remain the same. It is possible, however, that they will be changed. The federal Environmental Protection Agency (USEPA) has recently unveiled plans to enforce more stringent water quality standards. The targets of these proposed standards are the cancer-causing trihalomethanes. These new regulations would severely limit the amount of trihalomethanes allowed in drinking water, requiring many cities to convert from traditional sand filtration systems to a charcoal filtration method. These regulations would apply to cities with populations over 75,000. If these new regulations are enforced, the energy projections in this study would increase. The proposed standards would particularly affect New Orleans and St. Louis, reversing the projected downward trend in the amount of energy that will be required to supply water in these two cities.

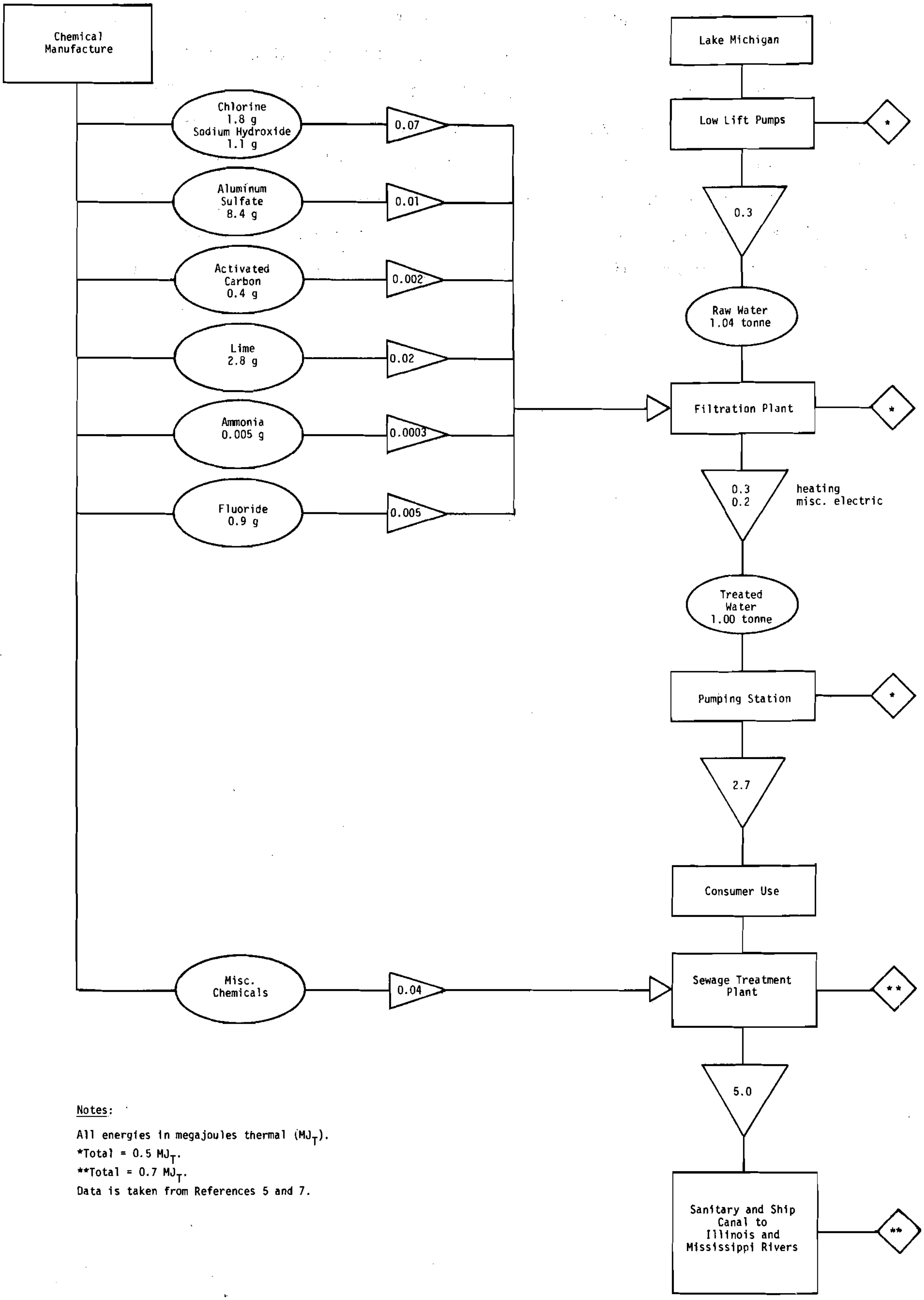
The additional energy that would be required to remove trihalomethanes would be consumed both for pumping and also as indirect energy in the form of material inputs such as chemicals and filter media. Consequently, to fully understand the energy impact of these new regulations, a method of analysis is required that accounts for both primary and indirect energy inputs. The analysis of the six major cities presented in this chapter considers only the primary energy inputs of fuel consumption and electrical requirements of the system.

Process energy analysis is one methodology whereby a process employed to provide a good or service may be disaggregated into sequential steps or stages and the inputs to each stage examined both in its physical dimension (units such as tons, kwh, and cu ft) and through the common denominator of its energy equivalent. Figure 15 presents a process analysis flow diagram of the Chicago Water Supply System. The symbols used in this flow diagram are figures conventional to process analysis. Rectangles represent process stages, and the ovals represent the quantity of both inputs to and outputs from individual process stages. For example, in Figure 15, 2.8 grams (g) of lime are required at the filtration plant and 1.04 metric tons (tonne) of raw water are discharged from the low lift pumps. The 2.8 g of lime required per tonne of water processed embody an equivalent energy of 0.02 MJ. Triangles indicate the primary energy requirements of the preceding process stage. Diamonds represent the energy embodied in the structure of the treatment facility itself.

Adding together the energy requirements in each triangle gives the total energy requirement of the process. All values in the triangles are normalized to a measure of MJ/tonne of water (3782 tonne = one mil gal of water).

Process analysis in its most complete state characterizes the provision of a good or service from the acquisition of raw material inputs followed by fabrication and consumption by consumers through to the disposal of the spent commodity. Figure 15 thus traces the flow of water from Lake Michigan through the water filtrations system to the consumer and beyond to its treatment at the sewage treatment plant and ultimate discharge into the Sanitary and Ship Canal. If one material input is substituted for another or if one production stage is replaced with a new technology, this kind of analysis makes possible a precise examination of the alterations in the system. In the case of the proposed water quality standards, the added materials and increased fuel or energy requirements can be indicated at each phase of the treatment process. By examining the energy and material flows in such a disaggregated way, the precise effects of these new regulations can be understood and ways of optimizing use of materials and energy resources can be devised.

The projections presented in this pilot study are based on a simplistic approach that does not consider all of the possible factors that influence



Notes:

All energies in megajoules thermal (MJ_T).

*Total = 0.5 MJ_T.

**Total = 0.7 MJ_T.

Data is taken from References 5 and 7.

Figure 15. Flow diagram for Chicago water showing where energy is consumed.

water consumption and the energy requirements to supply water. For example, economic constraints will influence water consumption. Water rights will influence available water supplies. The type of fuel used to operate water supply systems (coal vs natural gas) will influence the energy efficiency of supply water. While the projections presented in this study are based only on obvious trends, they do reveal regional differences. It is the general conclusion of this chapter that the amount of energy that will be needed to supply water in the future will be more a regional problem than a national concern.

3 SEWAGE TREATMENT

The method of analysis used for the energy requirements of sewage treatment differs markedly from that used in Chapter 2. Although survey forms were mailed to each of the cities included in the water supply study, the data returned were not sufficient to build a meaningful analysis. Instead, data were obtained through the generous cooperation of the federal Environmental Protection Agency (USEPA), delineating types of sewage plants in use across the country. Consequently, this analysis is a comprehensive assessment of all municipal treatment plants in operation. Instead of examining the energy consumption of specific municipalities, energy requirements for large regions of the country are portrayed and compared. Unlike the water-supply scenarios, the energy requirements per unit of sewage treated for each treatment system considered are fixed over time. The changes observed are in the number of treatment units required and in the changing mix of treatment types over time. The emerging patterns presented are influenced by population growth, increasing concern over the environment, and the industrial growth anticipated between 1977 and 1990.

Data Source

The data presented in this section to characterize the energy requirements for sewage treatment have been provided by the USEPA.[2] A state-by stage breakdown of the types of treatment plants in use in 1977 is assembled from the *1976 Needs Survey for Municipal Wastewater Treatment*. Five types of treatment plants--trickling filter (TF), activated sludge (AS), filtration (filt.), nitrification (nitr.), and ponds--are identified for each state of the United States. Each plant listed is placed in one of five capacity ranges: less than 5 mgd, 5 to 9.9 mgd, 10 to 19.9 mgd, 20 to 49 mgd, and greater than or equal to 50 mgd. The *1976 Needs Survey* records both plants presently in use and proposals for construction of new plants. Based on these proposals for new construction, a state-by-state listing of the types and capacities of plants expected to be in use in the year 1990 has also been prepared by the USEPA. Because federal funds necessary for construction of these proposed projects are limited, construction delays may occur, but at least 98 percent of the plants included in the 1990 list are almost certain to be on line by

1990. The USEPA is presently compiling the *1978 Needs Survey*, and data from this project should be available next year. The 1978 data will provide more accurate, updated information against which the calculations presented in this paper can be checked. In the listing of plants expected to be operating in 1990, a new type of treatment plant is included, advanced wastewater treatment (AWT). This category was excluded from the *1976 Needs Survey*, but the USEPA estimates that at least 200 of these plants will be constructed by 1990.[2] Because no data are available to indicate the exact number, size, or location of these plants, the following assumptions have been made. All AWTs in 1990 are included in the 10 to 19.9 mgd capacity range, and it is assumed that they will be built in densely populated industrial areas. Consequently, AWTs are assigned to geographic regions in proportion to the treatment capacity expected to exist in 1990 in the largest plants (greater than 50 mgd). The areas with the highest percentage of large capacity plants are assumed also to have the greatest number of AWTs. No AWTs are included in the 1977 list of sewage treatment plants.

Types of Sewage Treatment Plants

The types of treatment plants identified in this data may be used to achieve primary, secondary, tertiary, or advanced treatment. The degree of treatment employed depends upon the composition of the sewage inflow and the effluent quality desired. In very populous industrialized areas, for example, solids in the sewage are usually very concentrated, often containing heavy metals and other exotic contaminants. In addition, the effluent must often be of comparatively high water quality, as immediate reuse of water by downstream users often occurs, affording little opportunity for stream purification. Large urban areas therefore usually require higher degrees of sewage treatment than is necessary in rural areas, where much simpler forms of primary treatment are often adequate.

Primary treatment is accomplished with the smallest energy expenditure and involves the physical removal of 40 to 60 percent of the suspended solids by sedimentation. With secondary treatment, sewage usually undergoes an initial primary treatment stage. The primary stage effluent is then transferred to the secondary treatment stage, in which an even higher percentage of organic solids is removed. Biochemical reactions rather than physical sedimentation achieve improved water quality either by stabilizing organic solids or by decomposing them to inorganic solids. Of the treatment strategies identified in the *1976 Needs Survey*, ponds are the only primary treatment plants included. In some cases, however, algae and bacteria present in the water oxidize the organic wastes suspended in the sewage solution. This process of biological stabilization is actually a secondary treatment stage. Ponds then may achieve either primary or secondary treatment, depending on the specific situation. In the USEPA data, primary and secondary treatment ponds are not distinguished. The lowest energy requirement of all treatment strategies considered here is for treatment with ponds, as the sewage undergoes only sedimentation followed usually by chlorination of effluent.

Trickling filters and activated sludge plants provide secondary treatment, and activated sludge is the more common of the two treatment types. Wastewater treated in an activated sludge plant is mixed with oxygen and microorganisms to promote decomposition of the colloidal and dissolved organic matter into insoluble nonputrescible solids, carbon dioxide, water, and energy.[3] Once the wastewater has undergone aeration, it is removed to a settling basin, where biological solids fall to the bottom, forming a layer of sludge, while the clarified effluent is discharged. A portion of the bottom sludge layer, rich in microorganisms, is then reintroduced into the aeration step to accelerate biochemical degradation in the next quantity of influent treated. The sludge not returned to the aeration stage is treated and disposed of.

Sludge residue, an inevitable by-product of all sewage treatment strategies, must itself be treated to reduce its volume, remove bound water molecules, and transform putrescible organic solids to more stable organic and inorganic solids. Many methods are used; for example, anaerobic digestion is often used at activated sludge plants. In this sludge treatment operation, organic solids are consumed by a microbial population. The first phase of digestion produces volatile organic acids that are then attacked by methane bacteria.[4] In this second phase of digestion, approximately 60 percent methane gas is produced, which can be recaptured and used to heat the digesters and, in some cases, to generate electricity. Where sludge is not digested, heat drying, air drying, vacuum filtration, and chemical conditioning are sometimes used. Final disposal of the treated sludge is accomplished by incineration, landfill, or application as fertilizer or soil conditioner.

Trickling filters provide another type of secondary treatment which also utilizes microbial populations for oxidation of dissolved organic material and nutrients. The filter itself is normally a circular or rectangular bed of crushed rock 5 to 7 ft in depth. Growing on the surface of the filter is a biological or zoogleal film layer. Raw sewage is applied to the filter surface, where it is oxidized by the microbial population and then trickles through the rock media to a system of underdrains. These conduits carry the stabilized sewage to sedimentation tanks, where the suspended solids collect in a sludge layer. The supernatant flows out to surface water or to land, and the sludge is treated and disposed of by one of the methods previously mentioned. Cold weather poses problems for maintenance of the microbial layer on the filter media.

USEPA regulations governing water quality have become more stringent in recent years, particularly with respect to phosphorus and nitrogen. Effluent from secondary treatment processes must sometimes undergo tertiary treatment to meet these improved standards. The terms "tertiary" and "advanced treatment" are used interchangeably in much of the literature, but in the USEPA sewage-treatment-plant data, three separate types of tertiary treatment are distinguished: filtration, nitrification, and advanced wastewater treatment. Of these types, the simplest and least energy-intense is filtration, in which effluent from a secondary treatment process passes through fabric, filter paper, porous beds of granular material, sand, or some other filtering-straining medium.[3] The effluent after filtration has decreased phosphorus concentration, lower BOD (biological oxygen demand, i.e., amount of oxygen needed for biological oxidation of organic solids), and reduced turbidity.

A second, more complex method of tertiary treatment is nitrification. Wastewater, including effluent from secondary treatment, contains nitrogen in the form of the ammonium cation NH_4^+. Removal of this ammonia-nitrogen protects aquatic life from ammonia toxicity and reduces nitrogen nutrients that stimulate algal blooms.[3] The chemoautotrophic bacteria *nitrosomas* and *nitrobacter* operate in succession to oxidize nitrogenous compounds to nitrates

(NO_3). Two main nitrification systems are in use: suspended growth reactors, in which the chemoautotrophic bacteria and activated sludge effluent are slowly mixed, maintaining anaerobic conditions, and the ion exchange process, in which the NH_4^+ ion is replaced by Na^+ and Ca^{++} ions, which cause less environmental damage.[2]

The most energy-intensive treatment process presented in the following data is advanced wastewater treatment. USEPA data indicate that at present (1977) no AWTs are in operation in the United States. By 1990, however, it is estimated that at least 200 of these plants will be operating. The individual treatment units comprising advanced treatment will vary in different locations depending upon the particular water quality problems, but AWTs are characterized in the USEPA data as systems that provide secondary treatment, nitrification, chemical clarification, and filtration in sequential stages. Secondary treatment and nitrification have been discussed above. Chemical clarification reduces suspended solids in the effluent and removes phosphorus. With the addition of chemicals such as aluminum sulfate (alum), lime, and ferric chlorides, individual particles too small to be removed by physical methods such as sedimentation and filtration are agglomerated and may then be filtered out. The energy requirements for this extended treatment process is more than twice that of conventional secondary treatment.

Energy Requirements for Different Treatment Processes

The energy required to operate each of these primary, secondary, and tertiary treatment systems has been characterized by the consulting firm Culp/Wesner/Culp (G. M. Wesner, L. J. Ewing, Jr., T. S. Lineck, and D. J. Hinricks). The extensive data compiled by these researchers are presented in a draft paper titled "Energy Conservation in Municipal Wastewater Treatment," prepared on contract for the USEPA.[2] This paper is scheduled for review and final publication in the next few months. Tables 2-1(a) and 2-1(b) (titled "National Energy Requirements for Various Processes of Municipal Wastewater Treatment") of this draft paper present the electrical (kwh) and fossil fuel (Btu) energy requirements for each of the six treatment processes identified. For each capacity range, an average capacity figure is estimated to allow calculation of the energy required per plant as well as per mil gal. It was assumed in the

USEPA draft paper, and has been assumed in this paper as well, that each capacity range has the following average capacity:

Capacity Range	Assumed Average Capacity
less than 5 mgd	1 mgd
5 to 9.9 mgd	7.5 mgd
10 to 19.9 mgd	15 mgd
20 to 49.9 mgd	35 mgd
greater than 50 mgd	75 mgd

For purposes of this paper, the kwh and Btu energy requirements of the treatment plants have been combined and converted to a measure of the MJ required per plant annually and per mil gal annually. Table 34 gives the MJ equivalents for the primary and secondary energy requirements presented in Tables 2-1(a) and 2-1(b) of the USEPA report. The energy analysis presented in the following pages, however, interprets this energy data in a slightly different way. The USEPA draft data include under filtration and nitrification *only* the energy consumed in those individual phases of tertiary treatment. But because filtration and nitrification can only occur after secondary treatment has taken place, the energy assigned these plants in the following tables and graphs is the combined energy of secondary and tertiary treatment. For example, a 1 mgd filtration plant is considered in this paper to require annually the energy necessary to operate a 1 mgd activated sludge plant (6.5×10^6 MJ/plant) plus the energy required annually for filtration of the 1 mgd effluent (0.333×10^6 MJ/plant) to give a total energy requirement of 6.833×10^6 MJ to operate a 1 mgd filtration plant. Table 35 presents the energy requirements of the combined treatment categories as they are entered in the calculations for this present paper. In all categories, the energy requirement assigned to each type of plant is the same for both 1977 and 1990. The energy requirements in Tables 34 and 35 include not only the primary electrical and fossil fuel requirements for items such as pumping and heating, but also the indirect or secondary energy requirements for items such as the chemical inputs and filter media necessary in the treatment systems. Also included is the energy required for sludge disposal. The energy required for materials used in construction of these facilities is excluded from the energy calculations. Table 36 presents the direct and secondary energy requirements by treatment type instead of the

Table 34

Average Primary and Secondary Energy Requirements for Different Kinds of Treatment Plants Based on USEPA Draft Data

Plant Capacity	MJ 10^6/Plant Annually	MJ x 10^6/mil gal Annually
<u><5mgd (1 mgd)</u>		
TF	6.74	6.74
AS	6.50	6.50
Filt	0.33	0.33
Nitr	1.81	1.81
Ponds	3.74	3.74
<u>5-9.9 mgd (7.5 mgd)</u>		
TF	29.0	3.88
AS	34.5	4.60
Filt	2.87	0.37
Nitr	13.3	1.77
Ponds	26.3	3.51
<u>10-19.9 mgd (15 mgd)</u>		
TF	56.9	3.80
AS	69.0	4.60
Filt	5.4	0.36
Nitr	24.7	1.65
Ponds	72.5	5.23
AWT	158.0	10.54
<u>20-49.9 mgd (35 mgd)</u>		
TF	117.7	3.36
AS	149.9	4.28
Filt	13.9	0.40
Nitr	53.4	1.52
Ponds	129.7	3.71
<u>>50 mgd (75 mgd)</u>		
TF	226.9	3.03
AS	312.4	4.17
Filt	22.0	0.29
Nitr	121.8	1.62
Ponds	269.3	3.59

Table 35

Average Primary and Secondary Energy Requirements Used in This Report for Different Kinds of Treatment Plants

Plant Capacity	MJ 10^6/Plant Annually
<5 mgd (1 mgd)	
TF	6.74
AS	6.50
Filt	activated sludge + filtration 6.50 + 0.33 = 6.83
Nitr	activated sludge + 6.50 + 1.81 = 8.31
Ponds	3.74
5-9.9 mgd (7.5 mgd)	
TF	29.1
AS	34.5
Filt	activated sludge + filtration 34.52 + 2.77 = 37.30
Nitr	activated sludge + nitrification 34.5 + 13.3 = 47.8
Ponds	26.3
10-19.9 mgd (15 mgd)	
TF	56.9
AS	69.0
Filt	activated sludge + filtration 68.90 + 5.4 = 74.4
Nitr	activated sludge + nitrification 68.90 + 24.7 = 93.7
Ponds	78.50
AWT	158.0
20-49.9 mgd (35 mgd)	
TF	117.7
AS	149.9
Filt	activated sludge + filtration 149.9 + 13.9 = 163.8
Nitr	activated sludge + filtration 149.9 + 53.4 = 203.3 nitrification
Ponds	129.7
50 mgd (75 mgd)	
TF	227.0
AS	312.4
Filt	activated sludge + filtration 312.4 + 22.0 = 334.4
Nitr	activated sludge + filtration 312.4 + 121.8 = 434.3 nitrification
Ponds	269.3

Table 36

Average Direct and Secondary Energy Requirements for Different Kinds of Treatment Plants Based on USEPA Draft Data

Plant Capacity	MJ 10^6/Plant Annually	MJ x 10^6/mil gal Annually
<5 mgd (1 mgd)		
TF	3.53	3.53
AS	2.71	2.71
Filt	0.11	0.11
Nitr	0.59	0.59
Ponds	1.21	1.21
5-9.9 mgd (7.5 mgd)		
TF	13.96	1.73
AS	14.68	1.96
Filt	0.90	0.12
Nitr	4.30	0.57
Ponds	8.54	1.14
10-19.9 mgd (15 mgd)		
TF	25.46	1.70
AS	29.39	1.96
Filt	1.76	0.12
Nitr	8.02	0.53
Ponds	25.43	1.70
AWT	78.81	5.25
20-49.9 mgd (35 mgd)		
TF	53.46	1.53
AS	63.94	1.83
Filt	4.51	0.13
Nitr	17.31	0.49
Ponds	42.04	1.21
>50 mgd (75 mgd)		
TF	104.2	1.39
AS	133.3	1.78
Filt	7.1	0.095
Nitr	39.5	0.53
Ponds	87.3	1.16

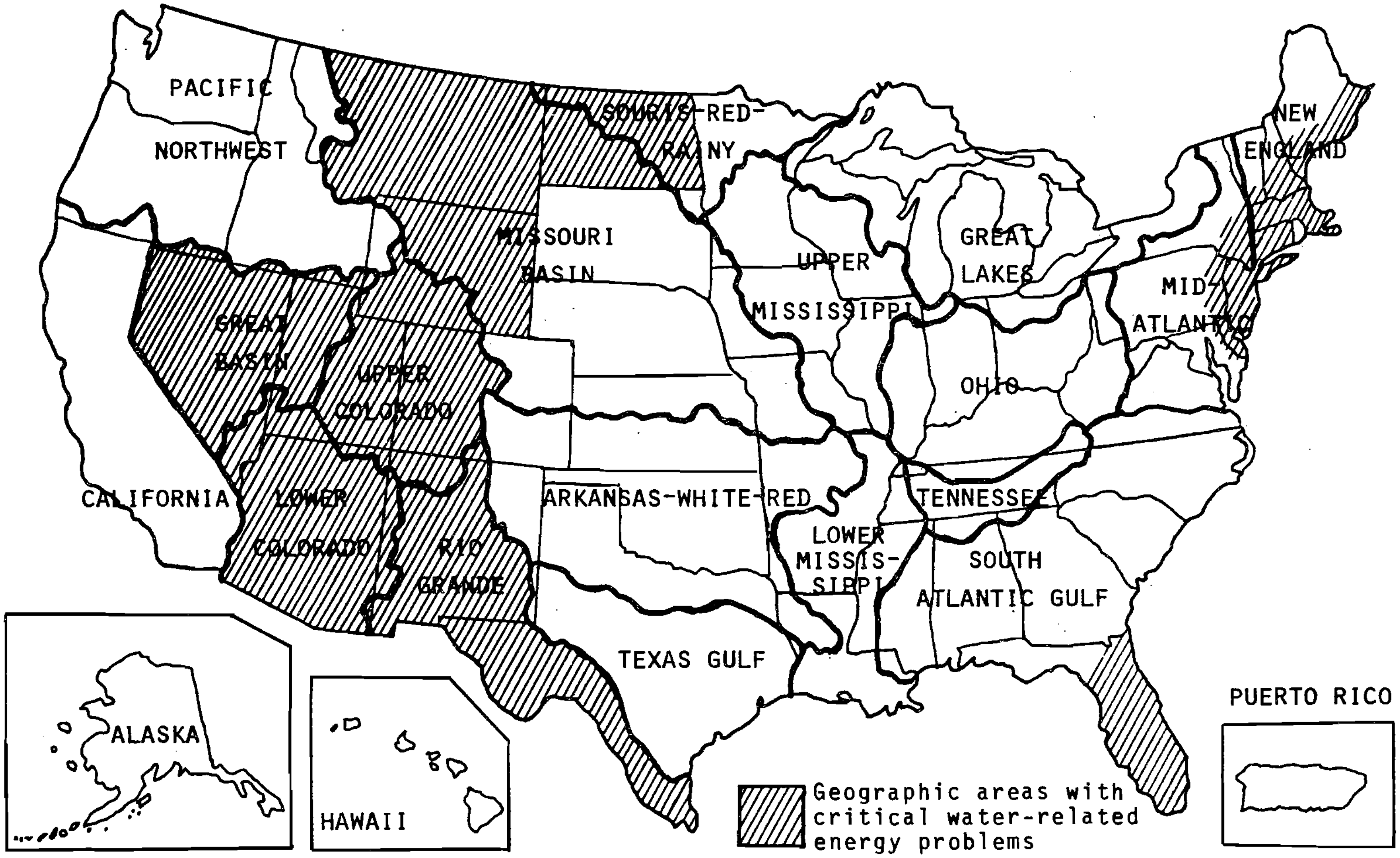
primary and secondary energy requirements calculated in Table 34. The higher energy values in Table 34 include the energy required to generate and transmit electrical energy. As discussed in the introduction, the direct energy of electricity does not include these energy inputs for production of electricity.

Organization of Geographic Regions

Although the USEPA sewage treatment data are disaggregated to single states, the analysis presented below describes geographical regions rather than individual states. States have been grouped together (except California) in rough correspondence with Water Resource Regions of the United States. Figure 16 delineates these water resource regions, which are defined by major river basins and watershed areas in the country. Figure 17 identifies the geographical regions used in this paper to analyze the energy requirements for sewage treatment in the United States. Unlike the Water Resource Regions of America, the borders of the geographical regions identified in this paper conform to state boundaries. As a result, in many cases parts of two or more water resource regions are combined to form the twelve geographical areas of sewage treatment analysis pictured in Figure 17. Region 7, the Lower Mississippi, combines the Lower Mississippi Water Resource Region with parts of the Souris-Red-Rainy and Great Lakes Water Resource Regions. The states encompassed by region 7 include Arkansas, Louisiana, Mississippi, and Missouri.

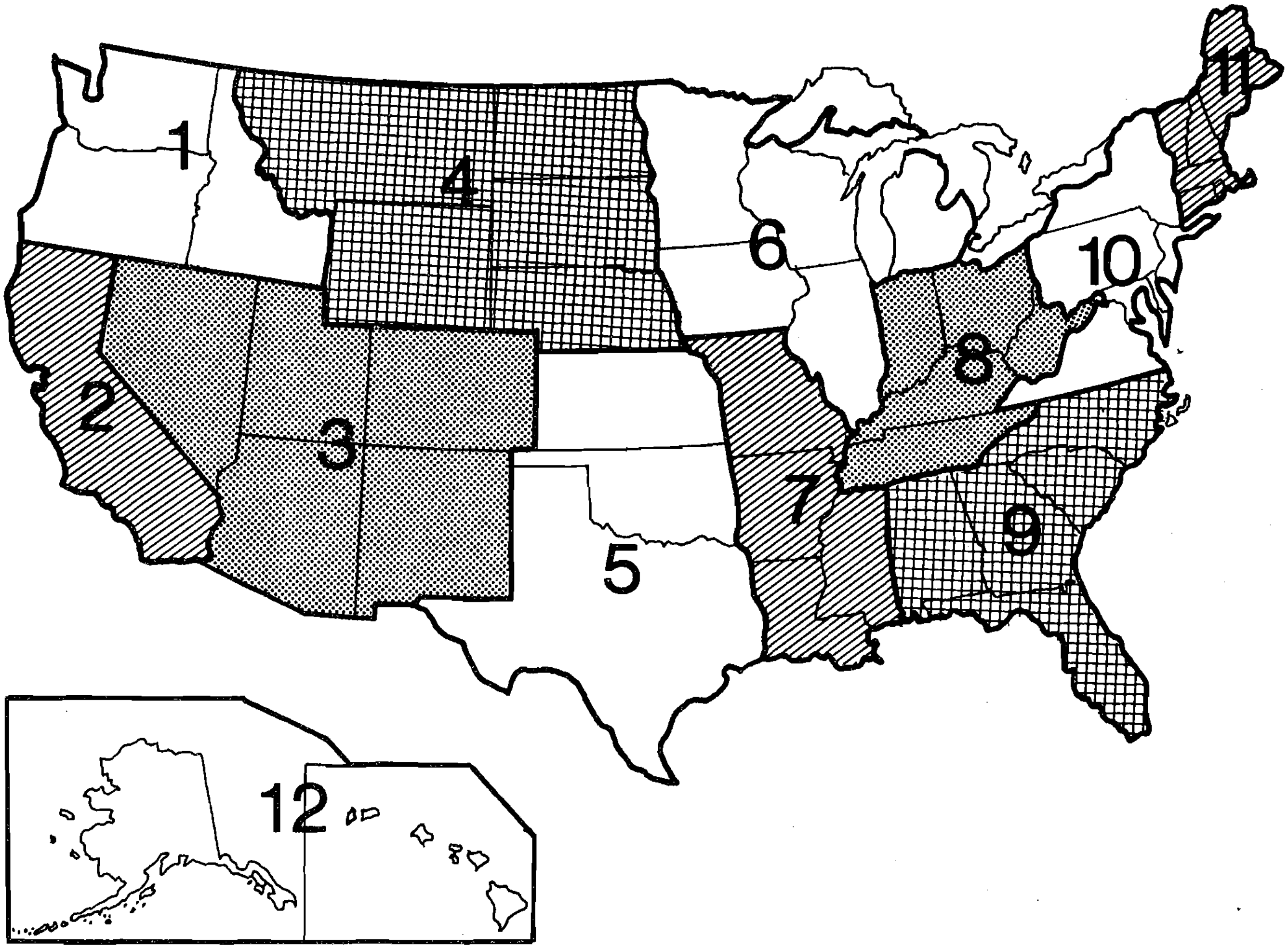
Regional Sewage Treatment Capacity

Tables 37 through 49 combine by geographic region the USEPA listing of sewage treatment plants of differing types and capacity sizes in each state. The states included in each regional table are listed below the regional title. Most of the activated sludge entries and a few entries of trickling filters and ponds are followed by a number in parenthesis. The first number is given in the USEPA data and represents the total number of plants in use, while the second number in parenthesis indicates those plants out of the total that provide only secondary treatment and are not combined with tertiary phases. Because filtration and nitrification units normally follow the activated sludge process, virtually all of the secondary plants assumed to be combined with tertiary units are activated sludge systems. These tables also give estimates of the total mgd capacity for each type of plant. These numbers are obtained by multiplying the average plant capacity in each of the capacity ranges by the



SOURCE: Water Resources Council. 1974. *Federal Energy Administration Project Independence Blueprint, Final Task Force Report, Water Requirements, Availabilities, Constraints, and Recommended Federal Actions.* Summary, Part I, p. 3.

Figure 16. Water resource regions.



REGION

1. PACIFIC NORTHWEST (Washington, Oregon, Idaho)
2. CALIFORNIA
3. GREAT BASIN, Lower Colorado, Upper Colorado, and Rio Grande (Nevada, Utah, Arizona, Colorado, New Mexico)
4. MISSOURI BASIN and Part of Souris-Red-Rainy (Montana, Wyoming, North Dakota, South Dakota, Nebraska)
5. ARKANSAS-WHITE-RED and Texas Gulf (Kansas, Oklahoma, Texas)
6. UPPER MISSISSIPPI with Part of Souris-Red-Rainy and Part of Great Lakes (Minnesota, Wisconsin, Iowa, Illinois, Michigan)
7. LOWER MISSISSIPPI (Arkansas, Louisiana, Mississippi)
8. OHIO and TENNESSEE (Indiana, Ohio, Kentucky, West Virginia, Tennessee)
9. SOUTH ATLANTIC GULF (Alabama, Georgia, South Carolina, North Carolina, Florida)
10. MID-ATLANTIC and Part of Great Lakes (New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia, District of Columbia)
11. NEW ENGLAND (Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island)
12. ALASKA and HAWAII

Figure 17. Energy for sewage treatment: Geographic regions of analysis based on water resource regions.

Table 37

Itemized Plants

Pacific Northwest
Washington, Oregon, Idaho

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	59	69	59	69	397.7	465.1
AS	74 (63)	344 (252)	63	252	409.5	1638.0
Filt	11	92	11	92	75.2	628.6
Nitr	0	0	0	0	0	0
Ponds	154	184	154	184	575.3	687.4
5-9.9 mgd						
TF	3	3	22.5	22.5	87.3	87.3
AS	10 (9)	24 (20)	67.5	150	310.7	690.5
Filt	1	4	7.5	30	37.3	149.2
Nitr	0	0	0	0	0	0
Ponds	1	1	7.5	7.5	26.4	26.4
10-19.9 mgd						
TF	2	2	30	30	113.9	113.9
AS	9 (7)	20 (16)	105	240	483.0	1103.9
Filt	2	4	30	60	148.8	297.7
Nitr	0	0	0	0	0	0
Ponds	1	1	15	15	78.5	78.5
AWT	0	8	0	120	0	1264.3
20-49.9 mgd						
TF	4	4	140	140	471.0	471.0
AS	2 (1)	9 (6)	35	210	149.9	899.5
Filt	1	3	35	105	163.8	491.5
Nitr	0	0	0	0	0	0
Ponds	5	5	175	175	648.7	648.7
>50 mgd						
TF	1	1	75	75	227.0	227.0
AS	2	5 (3)	150	225	624.9	937.3
Filt	0	1	0	75	0	334.4
Nitr	0	1	0	75	0	434.3
Ponds	0	0	0	0	0	0

Table 38
Itemized Plants
California

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	64	75	64	75	431.4	505.6
AS	145 (120)	296 (260)	120	260	780.0	1690.0
Filt	24	135	24	135	164.0	922.5
Nitr	1	1	1	1	8.3	8.3
Ponds	196	337	196	337	732.2	1259.0
5-9.9 mgd						
TF	17	19	127.5	142.5	494.6	552.7
AS	24 (19)	38 (30)	142.5	225.0	655.9	1035.7
Filt	5	16	37.5	120.0	186.5	596.7
Nitr	0	2	0	15	0	95.6
Ponds	23	24	172.5	180	606.1	632.4
10-19.9 mgd						
TF	5	6	75	90	284.7	341.6
AS	11 (5)	20 (7)	75	105	345.0	483.0
Filt	5	10	75	150	372.1	744.2
Nitr	1	3	15	45	93.8	281.3
Ponds	7	8	105	120	549.4	627.9
AWT	0	23	0	345	0	3635.0
20-49.9 mgd						
TF	4	5	140	175	471.0	588.7
AS	10 (9)	20 (1)	315	35	1349.2	149.9
Filt	1	13	35	455	163.8	2129.9
Nitr	0	6	0	210	0	1220.0
Ponds	2	2	70	70	259.5	259.5
>50 mgd						
TF	0	2	0	150	0	453.9
AS	4	13 (3)	300	225	1249.8	937.3
Filt	0	6	0	450	0	2006.4
Nitr	0	4	0	300	0	1737.1
Ponds	1	2	75	150	269.3	538.7

Table 39

Itemized Plants

Great Basin, Lower Colorado, Upper Colorado, and Rio Grande
Nevada, Utah, Arizona, Colorado, New Mexico

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) ($MJ \times 10^6$)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	48	58 (26)	48	26	323.6	175.3
AS	82 (62)	184 (16)	62	16	403.0	104.0
Filt	19	238	19	238	129.8	1626.2
Nitr	1	33	1	33	8.3	274.4
Ponds	242	393 (322)	242	322	904.1	1203.0
5-9.9 mgd						
TF	7	7 (6)	52.5	45	203.6	174.5
AS	7	12 (9)	52.5	67.5	241.7	310.7
Filt	0	3	0	22.5	0	111.9
Nitr	0	2	0	15.0	0	95.6
Ponds	4	4 (3)	30	22.5	105.4	79.1
10-19.9 mgd						
TF	5	5 (4)	75	60.0	284.7	227.8
AS	3	6 (1)	45	15	207.0	69.0
Filt	0	4	0	0	0	297.7
Nitr	0	2	0	0	0	187.5
Ponds	2	3	30	45	157.0	235.5
AWT	0	8	0	120	0	1264.3
20-49.9 mgd						
TF	4	4 (3)	140	105	471.0	353.2
AS	3	9 (5)	105	175	449.4	749.6
Filt	0	4	0	140	0	655.4
Nitr	0	1	0	35	0	203.3
Ponds	1	2	35	70	129.7	259.5
>50 mgd						
TF	1	1	75	75	227.0	227.0
AS	2	5 (2)	150	150	624.9	624.9
Filt	0	2	0	150	0	668.8
Nitr	0	1	0	75	0	434.3
Ponds	0	0	0	0	0	0

Table 40

Itemized Plants

Missouri Basin and Part of Souris-Red-Rainy
Montana, Wyoming, North Dakota, South Dakota, Nebraska

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	57	64 (59)	57	59	384.2	397.7
AS	63 (57)	171 (110)	57	110	370.5	715.0
Filt	6	61	6	61	41.0	416.8
Nitr	0	5	0	5	0	41.6
Ponds	681	932	681	932	2544.2	3481.9
5-9.9 mgd						
TF	1	1	7.5	7.5	29.1	29.1
AS	3	7 (5)	22.5	37.5	103.6	172.6
Filt	0	1	0	0	0	37.3
Nitr	0	1	0	0	0	47.8
Ponds	4	4	30.0	225	105.4	105.4
10-19.9 mgd						
TF	3	3	45	45	170.8	170.8
AS	3	3 (0)	45	45	207.0	0
Filt	0	2	0	30	0	148.8
Nitr	0	1	0	15	0	93.8
Ponds	0	1	0	15	0	78.5
AWT	0	2	0	30	0	316.1
20-49.9 mgd						
TF	1	1	35	35	117.7	117.7
AS	1	3	35	105	149.9	449.7
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
>50 mgd						
TF	0	0	0	0	0	0
AS	1 (0)	2 (0)	0	0	0	0
Filt	1	2	75	150	334.4	668.8
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0

Table 41

Itemized Plants

Arkansas-White-Red and Texas Gulf
Kansas, Oklahoma, Texas

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	326	330 (261)	326	261	2197.6	1759.4
AS	439 (420)	965 (507)	420	507	2730.0	3295.5
Filt	18	502	18	502	122.9	3430.2
Nitr	1	25	1	25	8.3	207.8
Ponds	819	942	819	942	3059.8	3519.3
5-9.9 mgd						
TF	19	20	142.5	150	552.7	581.8
AS	26 (22)	40 (20)	165.0	150	759.5	690.5
Filt	3	15	22.5	112.5	111.9	559.4
Nitr	1	5	7.5	37.5	47.8	239.0
Ponds	9	10	67.5	75	237.2	263.5
10-19.9 mgd						
TF	6	6 (5)	90	75	341.6	284.7
AS	9 (8)	14 (0)	120	0	552.0	0
Filt	1	11	15	165	74.4	818.6
Nitr	0	4	0	60	0	375.0
Ponds	3	4	45	60	235.5	314.0
AWT	0	16	0	240	0	2528.7
20-49.9 mgd						
TF	4	4	140	140	471.0	471.0
AS	11	14 (7)	385	245	1649.0	1049.4
Filt	0	4	0	140	0	655.4
Nitr	0	3	0	105	0	610.0
Ponds	4	4	140	140	518.9	518.9
>50 mgd						
TF	2	2 (1)	150	75	453.9	227.0
AS	6 (5)	9 (1)	375	75	1562.2	312.4
Filt	1	7	75	525	334.4	2340.8
Nitr	0	2	0	150	0	868.6
Ponds	1	1	75	75	269.3	269.3

Table 42

Itemized Plants

Upper Mississippi with Part Souris-Red-Rainy and Part of Great Lakes
Minnesota, Wisconsin, Iowa, Illinois, Michigan

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	630	687 (479)	630	479	4246.8	3228.9
AS	582 (481)	1107 (300)	481	300	3126.5	1950.0
Filt	99	947	99	947	676.5	6470.9
Nitr	2	68	2	68	16.6	565.3
Ponds	1000	2086	1000	2086	3736.0	7793.3
5-9.9 mgd						
TF	25	28	187.5	210	727.3	814.6
AS	35 (25)	59 (25)	187.5	187.5	863.1	863.1
Filt	9	26	67.5	195	335.6	969.6
Nitr	1	8	7.5	60	47.8	382.4
Ponds	5	10	37.5	75	131.8	263.5
10-19.9 mgd						
TF	11	12	165	180	626.4	683.3
AS	21 (17)	35 (18)	255	270	1172.9	1241.9
Filt	4	16	60	240	297.7	1190.7
Nitr	0	1	0	15	0	93.7
Ponds	5	5	75	75	392.4	392.4
AWT	0	28	0	420	0	4425.2
20-49.9 mgd						
TF	5 (4)	6	140	210	471.0	706.5
AS	23	35 (17)	805	595	3447.9	2548.5
Filt	1	15	35	525	163.8	2457.6
Nitr	0	3	0	105	0	610.0
Ponds	5	5	175	175	648.7	648.7
>50 mgd						
TF	2	2	150	150	453.9	453.9
AS	13	17 (9)	975	675	4061.8	2812.0
Filt	0	6	0	450	0	2006.4
Nitr	0	2	0	150	0	868.6
Ponds	1	1	75	75	269.3	269.3

Table 43

Itemized Plants

Lower Mississippi
Arkansas, Louisiana, Mississippi

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	135	146	135	146	910.0	984.2
AS	128 (108)	878 (463)	108	463	702.0	3009.5
Filt	20	405	20	405	136.7	2767.4
Nitr	0	10	0	10	0	83.1
Ponds	812	1086	812	1086	3033.6	4057.3
5-9.9 mgd						
TF	10 (8)	13 (12)	60	90	232.7	349.1
AS	11 (10)	28 (21)	75	157.5	345.2	725.0
Filt	3	8	22.5	60.0	111.9	298.3
Nitr	0	0	0	0	0	0
Ponds	10	10	75	75	263.5	263.5
10-19.9 mgd						
TF	4	5	60	75	227.8	284.7
AS	3	14 (11)	45	165	207.0	758.9
Filt	0	3	0	45	0	223.3
Nitr	0	0	0	0	0	0
Ponds	4	4	60	60	314.0	314.0
AWT	0	6	0	90	0	948.2
20-49.9 mgd						
TF	0	0	0	0	0	0
AS	3	10 (8)	105	280	449.7	1199.3
Filt	0	2	0	70	0	327.7
Nitr	0	0	0	0	0	0
Ponds	0	1	0	35	0	129.7
>50 mgd						
TF	0	0	0	0	0	0
AS	1	5	75	375	312.4	1562.2
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0

Table 44

Itemized Plants

Ohio and Tennessee
Indiana, Ohio, Kentucky, West Virginia, Tennessee

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	138	177 (172)	138	172	930.2	1159.4
AS	569 (492)	1912 (870)	492	870	3198.0	5655.0
Filt	72	969	72	969	492.0	6621.2
Nitr	5	99	5	99	41.6	823.1
Ponds	248	580 (559)	248	559	926.5	2088.4
5-9.9 mgd						
TF	5	9	37.5	67.5	145.5	261.8
AS	45 (41)	64 (25)	307.5	187.5	1415.5	863.1
Filt	4	33	30.0	247.5	149.2	1230.7
Nitr	0	6	0	0	0	286.8
Ponds	5	10	37.5	75	131.8	263.5
10-19.9 mgd						
TF	2	2 (1)	30	15	113.9	56.9
AS	22 (18)	31 (11)	270	165	1241.9	758.9
Filt	2	18	30	270	148.8	1339.6
Nitr	2	3	30	45	187.5	281.3
Ponds	2	4	30	60	157.0	314.0
AWT	0	32	0	480	0	5057.3
20-49.9 mgd						
TF	1	2	35	70	117.7	235.5
AS	11 (10)	20 (7)	350	245	1499.1	1049.4
Filt	0	9	0	315	0	1474.6
Nitr	1	4	35	140	203.3	813.3
Ponds	1	2	35	70	129.7	259.5
>50 mgd						
TF	0	0	0	0	0	0
AS	14 (13)	21 (10)	975	750	4061.8	3124.5
Filt	1	10	75	750	334.4	3344.1
Nitr	0	1	0	75	0	434.3
Ponds	2	2	150	150	538.7	538.7

Table 45

Itemized Plants

South Atlantic Gulf
Alabama, Georgia, South Carolina, North Carolina, Florida

Plant Capacity (mgd)	Number of Plants 1977	Number of Plants 1990	Total Estimate (mgd) 1977	Total Estimate (mgd) 1990	Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6) 1977	Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6) 1990
<4.9 mgd						
TF	216	236 (214)	216	214	1456.0	1442.6
AS	404 (364)	1195 (451)	364	451	2366.0	2931.0
Filt	36	625	36	625	246.0	4270.6
Nitr	4	141	4	141	33.2	1172.3
Ponds	501	617	501	617	1871.7	2305.1
5-9.8 mgd						
TF	29	29 (25)	217.5	187.5	843.7	727.3
AS	53 (47)	94 (28)	352.5	210.0	1622.6	966.7
Filt	4	47	30	352.5	149.2	1752.8
Nitr	2	23	15	172.5	95.6	1099.4
Ponds	14	25	105	187.5	368.9	658.8
10-19.9 mgd						
TF	22	22	330	330	1252.7	1252.7
AS	43 (38)	60 (22)	570	330	2621.8	1517.9
Filt	4	24	50	360	297.7	1786.1
Nitr	1	14	15	210	93.8	1312.5
Ponds	7	9	105	135	549.4	706.4
AWT	0	8	0	120	0	1264.3
20-49.9 mgd						
TF	11	13 (12)	385	420	1295.2	1413.0
AS	27 (19)	36 (6)	665	210	2848.3	899.5
Filt	5	20	175	700	819.2	3276.8
Nitr	3	11	105	385	610.0	2236.7
Ponds	4	5	140	175	518.9	648.7
>50 mgd						
TF	0	0	0	0	0	0
AS	3 (2)	6 (3)	150	225	624.9	937.3
Filt	0	1	0	75	0	334.4
Nitr	1	2	75	150	434.3	868.6
Ponds	0	0	0	0	0	0

Table 46

Itemized Plants

Mid-Atlantic and Part of Great Lakes
New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia, District of Columbia

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	297 (278)	355	278	355	1874.0	2393.1
AS	720 (458)	2187 (1254)	458	1254	2977.0	8151.0
Filt	278	859	278	859	1899.6	5869.5
Nitr	3	74	3	74	24.9	615.2
Ponds	222	313	222	313	829.4	1169.4
5-9.9 mgd						
TF	27	28	202	210	785.5	814.6
AS	50 (42)	107 (43)	315	322.5	1450.0	1484.5
Filt	8	47	60	352.5	298.3	1752.8
Nitr	0	17	0	127.5	0	812.6
Ponds	4	10	30	75.0	105.4	263.5
10-19.9 mgd						
TF	4	5	60	75	227.8	284.7
AS	22 (21)	54 (29)	315	435	1448.9	2000.9
Filt	1	16	15	240	74.4	1190.7
Nitr	0	9	0	135	0	843.8
Ponds	1	2	15	30	78.5	157.0
AWT	0	58	0	870	0	9166.4
20-49.9 mgd						
TF	5	5	175	175	588.7	588.7
AS	23 (20)	50 (27)	700	945	2998.2	4047.6
Filt	2	17	70	595	327.7	2785.3
Nitr	1	6	35	210	203.3	1220.0
Ponds	0	1	0	35	0	129.7
> 50 mgd						
TF	2	2	150	150	453.9	453.9
AS	21	38 (25)	1575	1875	6561.4	7811.1
Filt	0	10	0	750	0	3344.1
Nitr	0	3	0	225	0	1302.9
Ponds	1	2	75	150	269.3	538.7

Table 47

Itemized Plants

New England
Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island

Plant Capacity (mgd)	Number of Plants 1977		Number of Plants 1990		Total Estimate (mgd) 1977	Total Estimate (mgd) 1990	Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6) 1977	Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6) 1990
<4.9 mgd								
TF	24		28		24	28	161.8	188.7
AS	161	(124)	405	(245)	124	245	806.0	1592.5
Filt	37		131		37	131	252.8	895.1
Nitr	0		29		0	29	0	241.1
Ponds	37		109		37	109	138.2	407.2
5-9.9 mgd								
TF	4		5		30	37.5	116.4	145.5
AS	20	(18)	38	(10)	135	75	621.4	345.2
Filt	2		13		15	97.5	74.6	484.8
Nitr	0		15		0	112.5	0	717.0
Ponds	0		0		0	0	0	0
10-19.9 mgd								
TF	1		1		15	15	56.9	56.9
AS	17	(16)	29	(19)	240	285	1103.9	1310.9
Filt	0		6		0	90	0	446.5
Nitr	1		4		15	60	93.8	375.0
Ponds	0		0		0	0	0	0
AWT	0		10		0	150	0	1580.4
20-49.9 mgd								
TF	1		1		35	35	117.7	117.7
AS	6		15	(10)	210	350	899.5	1499.1
Filt	0		3		0	105	0	491.5
Nitr	0		2		0	70	0	406.7
Ponds	0		0		0	0	0	0
>50 mgd								
TF	0		0		0	0	0	0
AS	3		7	(6)	225	450	937.3	1874.7
Filt	0		1		0	75	0	334.4
Nitr	0		0		0	0	0	0
Ponds	0		0		0	0	0	0

Table 48
Itemized Plants
Alaska

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	0	1	0	1	0	6.7
AS	7	19 (18)	7	18	45.5	117.0
Filt	0	1	0	1	0	6.8
Nitr	0	0	0	0	0	0
Ponds	3	103	3	103	11.2	384.8
5-9.9 mgd						
TF	0	0	0	0	0	0
AS	0	1	0	7.5	0	34.5
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
10-19.9 mgd						
TF	0	0	0	0	0	0
AS	0	0	0	0	0	0
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
AWT	0	0	0		0	
20-49.9 mgd						
TF	0	0	0	0	0	0
AS	0	1	0	35	0	149.9
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
>50 mgd						
TF	0	0	0	0	0	0
AS	0	0	0	0	0	0
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0

Table 49
Itemized Plants
Hawaii

Plant Capacity (mgd)	Number of Plants		Total Estimate (mgd)		Annual Energy Requirement (Primary and Secondary Energy) (MJ x 10^6)	
	1977	1990	1977	1990	1977	1990
<4.9 mgd						
TF	1	1	1	1	6.7	6.7
AS	12	38 (36)	12	36	78.0	234.0
Filt	0	2	0	2	0	13.7
Nitr	0	0	0	0	0	0
Ponds	2	2	2	2	7.5	7.5
5-9.9 mgd						
TF	1	2	7.5	15	29.1	58.2
AS	1	6 (4)	7.5	30	34.5	138.1
Filt	0	2	0	15	0	74.6
Nitr	0	0	0	0	0	0
Ponds	0	1	0	7.5	0	26.4
10-19.9 mgd						
TF	1	1	15	15	56.9	56.9
AS	0	1	0	15	0	69.0
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
AWT	0	1	0	15	0	158.0
20-49.9 mgd						
TF	0	0	0	0	0	0
AS	0	0	0	0	0	0
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0
>50 mgd						
TF	0	0	0	0	0	0
AS	0	1	0	75	0	312.4
Filt	0	0	0	0	0	0
Nitr	0	0	0	0	0	0
Ponds	0	0	0	0	0	0

number of plants in that range. The average capacities for each capacity range are listed in the first section (data source). In Table 37, "The Pacific Northwest," the total mgd capacity estimated for trickling filters less than 5 mgd is 59 mgd and 69 mgd in the years 1977 and 1990 respectively, since plants in this capacity range are assumed to have an average capacity of 1 mgd. In this same capacity range, the estimated capacity for activated sludge is estimated at 63 mgd in 1977 and at 252 mgd in 1990. It is the number in parenthesis that is used to estimate total capacity for activated sludge, as the capacity of all secondary activated sludge plants combined with tertiary treatment is included in the capacity estimates for tertiary treatment. For all treatment types combined, the capacity available in the largest plants (greater than 50 mgd) is compared regionally with the capacity available in the smallest plants (less than 5 mgd) in Table 50.

Regional Energy Requirements for Sewage Treatment by Treatment Type

Tables 37 through 49 also show the estimated energy requirement for each plant type in each capacity range. These estimates of the total number of MJ required annually for each plant category are obtained by multiplying the number of plants times the energy requirement per plant indicated in Table 36. As discussed earlier, the energy requirement for filtration and nitrification includes the energy required not only in these tertiary steps but also in the preceding secondary treatment assumed here to be activated sludge. To consider the energy required for tertiary treatment apart from secondary treatment, Table 35 can be used, as the energy requirement for filtration and nitrification plants listed in this table applies only to the tertiary treatment phase. In all subsequent analysis and discussion, the energy requirements for filtration, nitrification, and AWT include the energy for all stages of treatment through tertiary.

Tables 51 through 62 present the total estimated capacity (mgd) and the total annual energy requirement summed over all capacity ranges. In the Pacfic Northwest (Table 51), for example, the energy required in 1977 for trickling filters in the less-than-5-mgd range (397.7 MJ x 10^6) is added to the energy required for trickling filters in the capacity range 5 to 9.9 mgd (87.3 x 10^6 MJ), and so on until all capacity ranges have been added together, giving a total energy requirement for trickling filters in 1977 in the Pacific Northwest

Table 50

Regional Distribution of Small Capacity and Large Capacity Sewage Treatment Plants

	Capacity ≤ 5 mgd				Capacity ≤ 5 mgd			
	1977 (mgd)	Percent of Total Capacity	1990 (mgd)	Percent of Total Capacity	1977 (mgd)	Percent of Total Capacity	1990 (mgd)	Percent of Total Capacity
Pacific Northwest	287	24	597	25	225	19	450	19
California	405	19	808	18	375	17	1275	28
Great Basin	372	32	635	21	225	19	450	15
Missouri Basin	801	73	1167	61	75	7	150	8
Arkansas-White-Red	1584	44	2237	44	675	20	900	18
Upper Mississippi	2212	39	3880	44	1200	21	1500	17
Lower Mississippi	1075	65	2110	57	75	5	375	10
Ohio and Tennessee	955	28	2669	39	1200	35	1725	25
South Atlantic Gulf	1121	24	2048	29	225	5	450	6
Mid-Atlantic	1239	25	2855	26	1800	36	3150	29
New England	222	19	542	21	225	20	525	21
Alaska and Hawaii	25	45	164	42	0	0	75	19
United States	10298	34	19612	34	6300	21	11025	19

Table 51

Primary and Secondary Energy and Capacity Summary
Pacific Northwest
Washington, Oregon, Idaho

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	326.5	336.5	1296.9	1364.3
Activated Sludge	420.5	1077.0	1978.0	5269.2
Secondary & Filtration	83.5	362.0	425.1	1901.4
Secondary & Nitrification	0	90	0	434.3
Ponds	351.5	381.5	1328.9	1441.0
AWT	0	120	0	1264.3
Total for all treatment types	1182.0	2367.0	5028.9	11674.5

Table 52

Primary and Secondary Energy and Capacity Summary
California

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling Filter	406.5	632.5	1681.7	2442.5
Activated Sludge	952.5	850.0	4379.9	4295.1
Secondary & Filtration	171.5	1310.0	886.4	6399.7
Secondary & Nitrification	16.0	571.0	102.1	3342.3
Ponds	618.5	857.0	2416.5	3317.5
AWT	0	345.0	0	3635.0
Total for all treatment types	2165.0	4565.5	9466.6	23432.1

Table 53

Primary and Secondary Energy and Capacity Summary
Great Basin
Lower Colorado, Upper Colorado and Rio Grande
Nevada, Utah, Arizona, New Mexico, Colorado

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	390.5	311.0	1509.9	1157.8
Activated Sludge	414.5	423.5	1926.3	1858.2
Secondary & Filtration	19.0	550.5	129.8	3360.0
Secondary & Nitrification	1.0	158.0	8.3	1195.1
Ponds	337.0	864.5	1296.2	1777.1
AWT	0	120.0	0	1264.3
Total for all treatment types	1162.0	2427.5	4870.5	10612.5

Table 54

Primary and Secondary Energy and Capacity Summary
Missouri Basin and Part of Souris-Red-Rainy
Montana, Wyoming, North Dakota, South Dakota, Nebraska

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	144.5	146.5	701.8	715.3
Activated Sludge	159.5	297.5	831.0	1337.3
Secondary & Filtration	81	241	375.4	1271.7
Secondary & Nitrification	0	20	0	183.2
Ponds	711	1172	2649.6	3665.8
AWT	0	30	0	316.1
Total for all treatment types	1096.0	1907.0	4557.8	7489.4

Table 55

Primary and Secondary Energy and Capacity Summary
Arkansas-White-Red and Texas Gulf
Kansas, Oklahoma, Texas

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling Filter	848.5	701.0	3986.8	3323.9
Activated Sludge	1465.0	977.0	7252.7	5347.8
Secondary & Filtration	130.5	1444.5	642.9	8742.8
Secondary & Nitrification	8.5	377.5	56.1	2568.5
Ponds	1146.5	1292.0	4320.7	4885.0
AWT	0	240	0	2528.7
Total for all treatment types	3599.0	5032.0	16259.2	27396.7

Table 56

Primary and Secondary Energy and Capacity Summary
Upper Mississippi, with part of Souris-Red-Rainy and Part of Great Lakes
Minnesota, Wisconsin, Iowa, Illinois, Michigan

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	1272.5	1229.0	6525.4	5887.2
Activated Sludge	2703.5	2027.5	12672.2	9415.5
Secondary & Filtration	261.5	2357.0	1473.6	13095.2
Secondary & Nitrification	9.5	398.0	64.4	2520.0
Ponds	1362.5	2486.0	5178.2	9367.2
AWT	0	420.0	0	4425.2
Total for all treatment types	5609.5	8917.5	25913.8	44710.3

Table 57

Primary and Secondary Energy and Capacity Summary
Lower Mississippi
Arkansas, Louisiana, Mississippi, Missouri

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	255	311	1370.5	1618.0
Activated Sludge	408	1440.5	2016.3	7254.9
Secondary & Filtration	42.5	580	248.6	3616.7
Secondary & Nitrification	0	10	0	83.1
Ponds	947	1256.0	3611.0	4764.5
AWT	0	90	0	948.2
Total for all treatment types	1652.5	3687.5	7246.4	18285.4

Table 58

Primary and Secondary Energy and Capacity Summary
Ohio and Tennessee
Indiana, Ohio, Kentucky, West Virginia, Tennessee

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	240.5	324.5	1307.3	1713.6
Activated Sludge	2394.5	2217.5	11416.3	11451.5
Secondary & Filtration	207	2551.5	1124.4	14010.2
Secondary & Nitrification	70	359	432.4	2638.2
Ponds	500.5	914	1883.7	3464.1
AWT	0	480	0	5057.3
Total for all treatment types	3412.5	6846.5	16164.1	38334.9

Table 59
Primary and Secondary Energy and Capacity Summary
South Atlantic Gulf
Alabama, Georgia, South Carolina, North Carolina, Florida

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	1148.5	1151.5	4847.6	4853.6
Activated Sludge	2101.5	1426.0	10083.6	7252.9
Secondary & Filtration	301.0	2112.5	1512.1	11420.7
Secondary & Nitrification	214	1058.5	1266.6	6689.5
Ponds	851	1114.5	3308.2	4319.0
AWT	0	120	0	1264.3
Total for all treatment types	4616.0	6983.0	21018.1	35800.0

Table 60
Primary and Secondary Energy and Capacity Summary
Mid-Atlantic and Part of Great Lakes
New York, Pennsylvania, New Jersey, Delaware,
Maryland, Virginia, District of Columbia

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	865	965	3929.9	4535.0
Activated Sludge	3363	4831.5	15435.5	23495.1
Secondary & Filtration	423	2796.5	2600.0	14942.4
Secondary & Nitrification	38	771.5	228.2	4794.5
Ponds	342	603.0	1282.6	2258.3
AWT	0	870.0	0	9166.4
Total for all treatment types	5031.0	10837.5	23476.2	59191.7

Table 61

Primary and Secondary Energy and Capacity Summary
New England
Maine, Vermont, New Hampshire, Massachusetts,
Connecticut, Rhode Island

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	104	115.5	452.8	508.8
Activated Sludge	934	1405.0	4368.1	6622.4
Secondary & Filtration	52	498.5	327.4	2652.3
Secondary & Nitrification	15	271.5	93.8	1739.8
Ponds	37	109	138.2	407.2
AWT	0	150	0	1580.4
Total for all treatment types	1142.0	2549.5	5380.3	13510.9

Table 62

Primary and Secondary Energy and Capacity Summary
Alaska and Hawaii

Treatment Type	Total Capacity mgd		Annual Energy Requirement MJ x 10^6	
	1977	1990	1977	1990
Trickling filter	23.5	32	92.7	128.5
Activated Sludge	26.5	216.5	158.0	1054.9
Secondary & Filtration	0	18	0	95.1
Secondary & Nitrification	0	0	0	0
Ponds	5	112.5	18.7	418.7
AWT	0	15	0	158.0
Total for all treatment types	55.0	394.0	269.4	1855.2

of 5028.9 x 10^6 MJ annually. The energy data in these summary Tables 51 through 62 are presented graphically in Figures 18 through 29. The histograms in these figures depict the increase in total MJ required annually for different types of sewage treatment in different regions of the country between 1977 and 1990. In some of the figures, the energy required for activated sludge declines between 1977 and 1990. This decline does not result from a decrease in the energy required per mil gal, as the energy requirements per unit of sewage treated are assumed to be the same in 1977 and in 1990. Nor does this decline in energy represent a phasing out of treatment plants, as all the plants in operation in 1977 are also expected to be operating in 1990. The decline in energy for activated sludge where it occurs reflects the upgrading of a secondary treatment process to a tertiary treatment process. All declines in energy for the activated sludge treatment are matched by identical increases in the energy required in the filtration and nitrification categories.

It can be observed from the data in Tables 51 through 62 and the corresponding histograms that in most regions of the country a large increase in the energy required for tertiary treatment will occur between 1977 and 1990.

For each of the regions, the following treatment processes will require the greatest increase in energy between 1977 and 1990.

Region	Treatment Types Requiring the Greatest Increase in Energy
Pacific Northwest	activated sludge and filtration
California	filtration and nitrification
Great Basin	filtration and nitrification
Missouri Basin	ponds and filtration
Arkansas-White-Red	filtration and nitrification
Upper Mississippi	ponds and filtration
Lower Mississippi	activated sludge and filtration
Ohio and Tennessee	filtration and nitrification
South Atlantic Gulf	filtration and nitrification
Mid-Atlantic	activated sludge and filtration
New England	activated sludge and filtration
Alaska and Hawaii	ponds and activated sludge

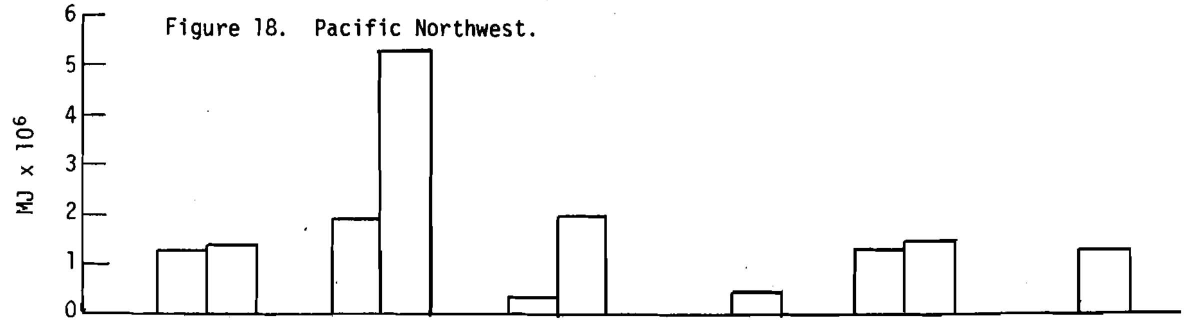


Figure 18. Pacific Northwest.

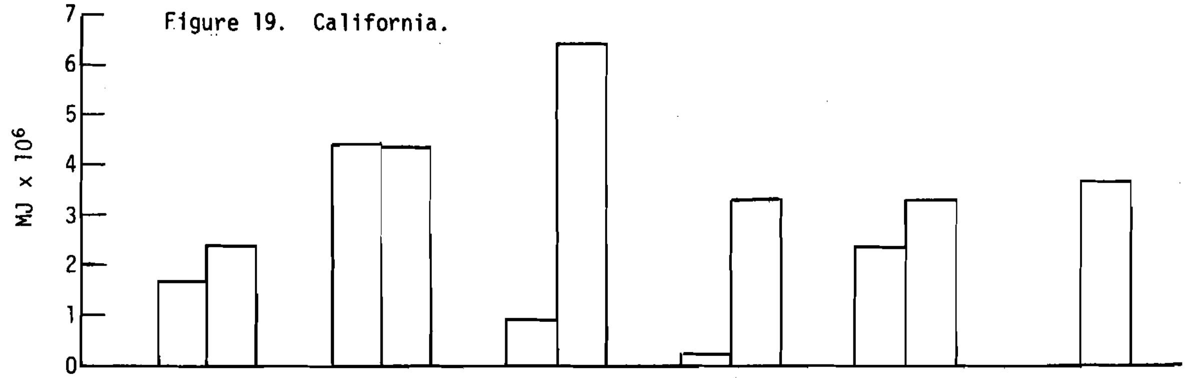


Figure 19. California.

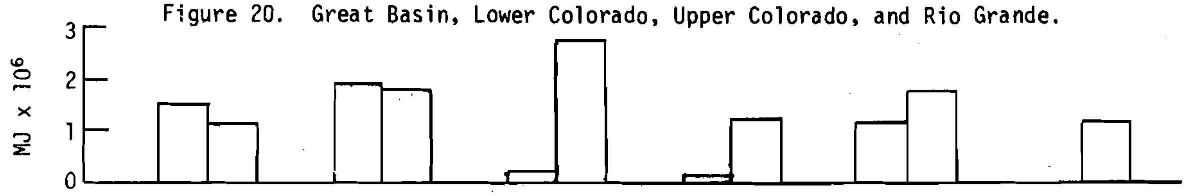


Figure 20. Great Basin, Lower Colorado, Upper Colorado, and Rio Grande.

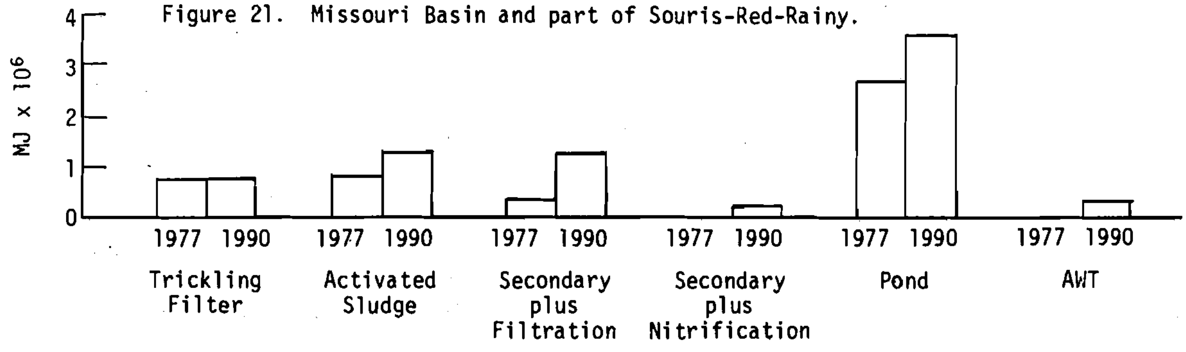


Figure 21. Missouri Basin and part of Souris-Red-Rainy.

Figures 18 through 21. Primary and secondary energy consumption by type of sewage treatment in various areas.

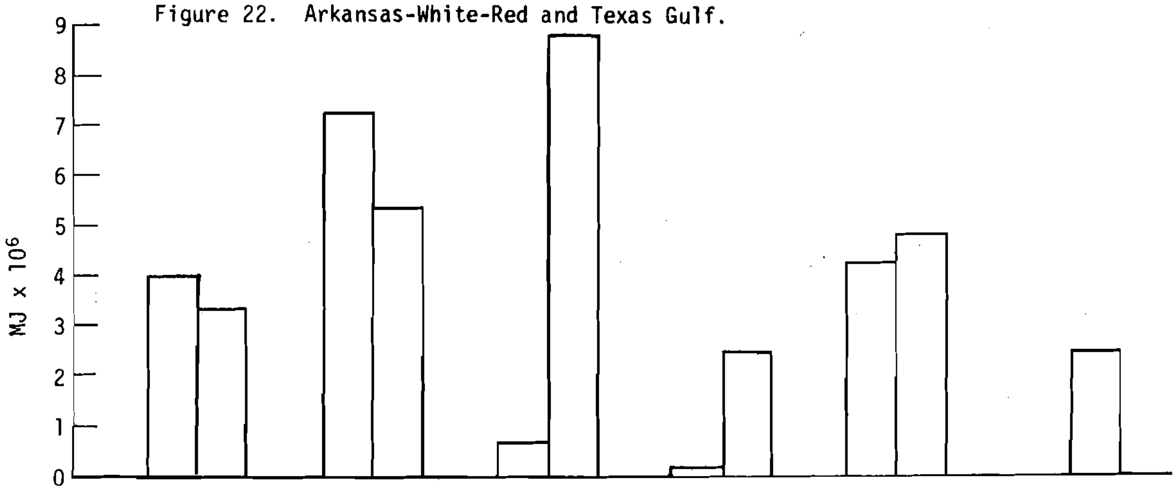


Figure 22. Arkansas-White-Red and Texas Gulf.

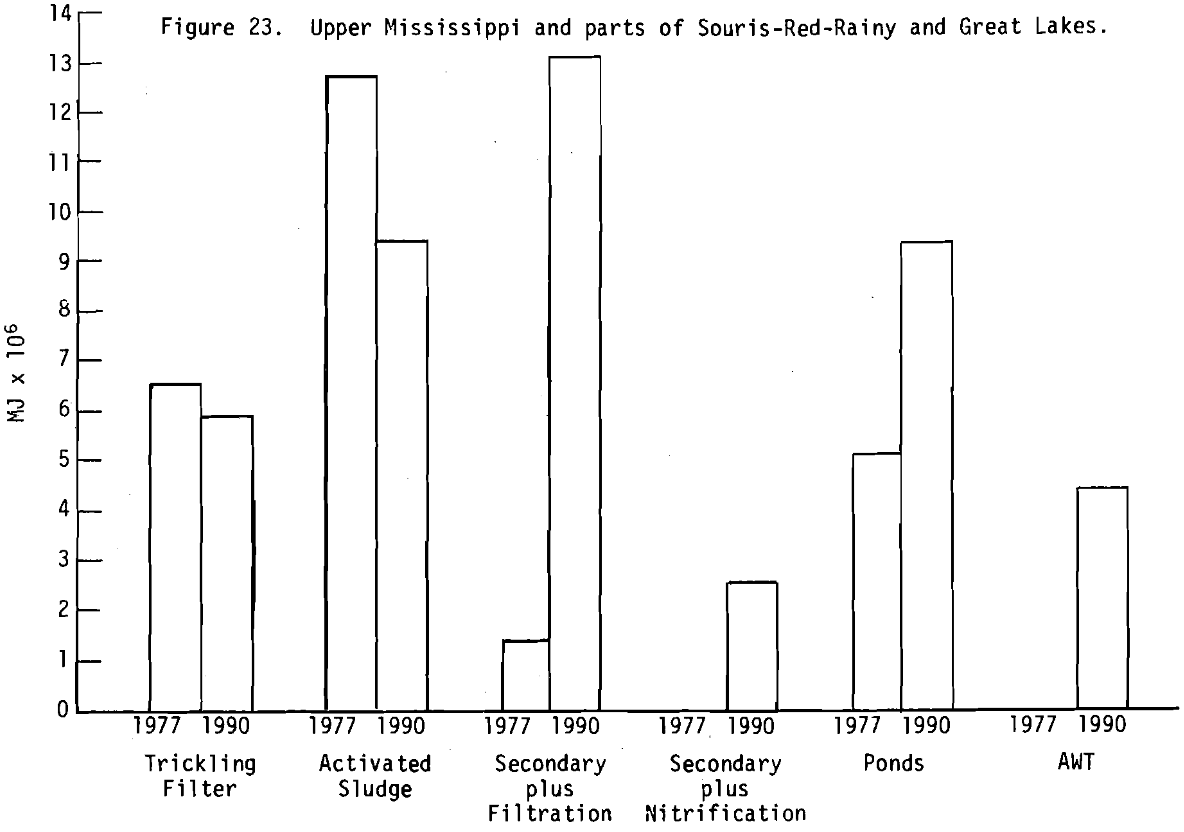


Figure 23. Upper Mississippi and parts of Souris-Red-Rainy and Great Lakes.

Figures 22 and 23. Primary and secondary energy consumption by type of sewage treatment in various areas.

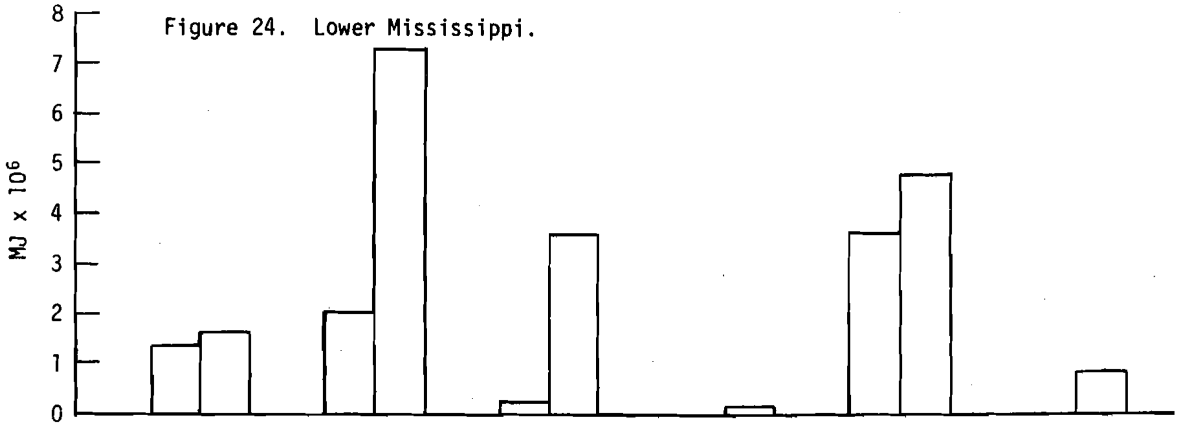
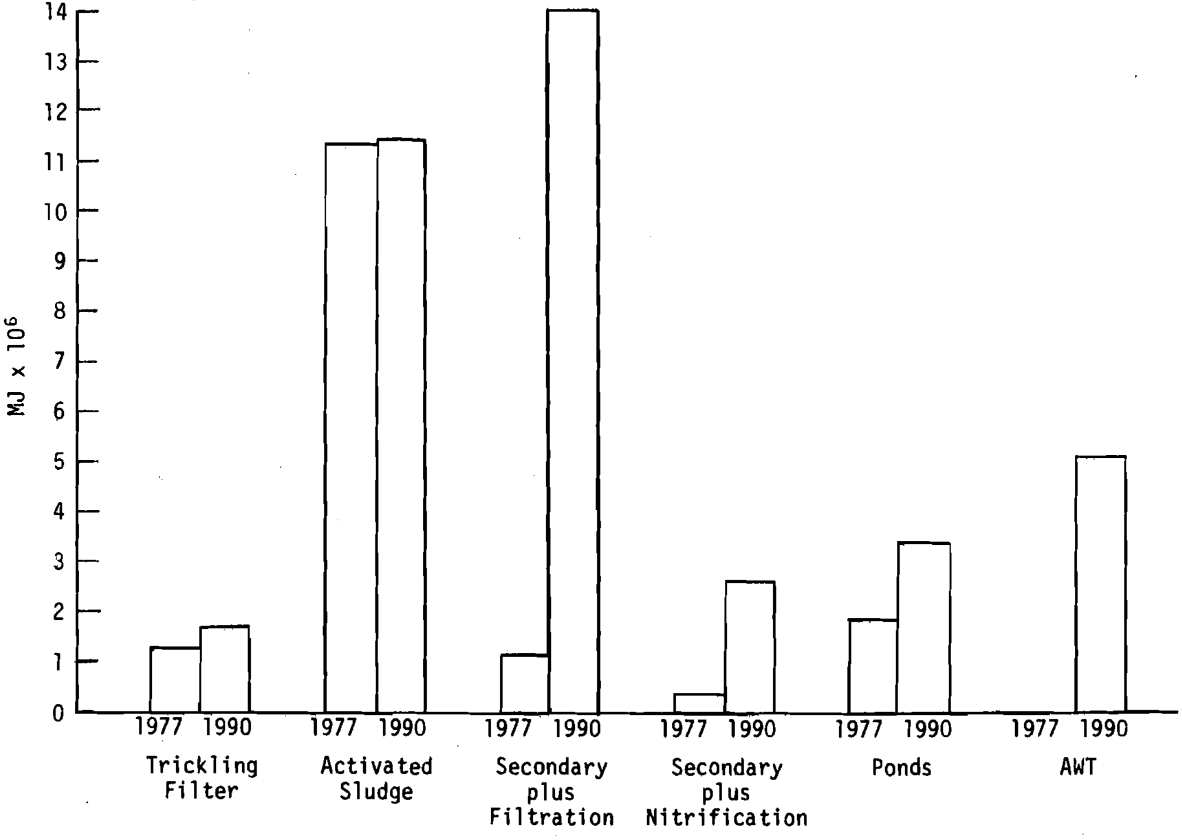


Figure 24. Lower Mississippi.

Figure 25. Ohio and Tennessee.



Figures 24 and 25. Primary and secondary energy consumption by type of sewage treatment in various areas.

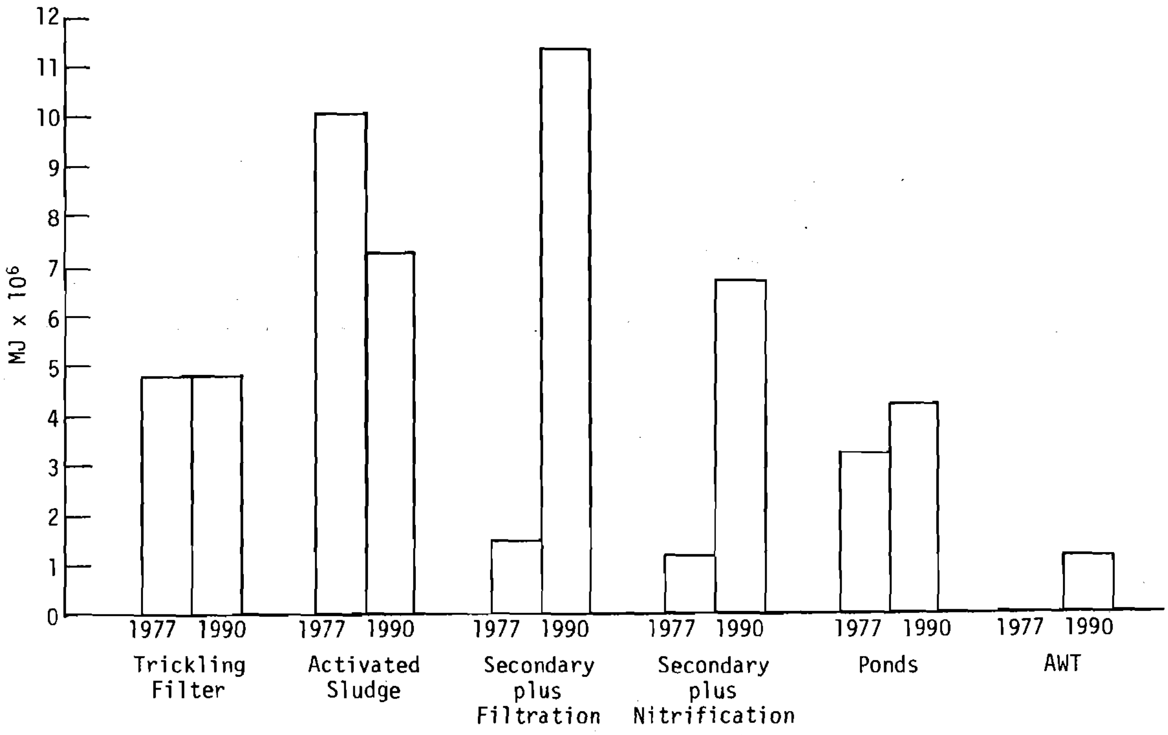


Figure 26. Primary and secondary energy consumption by type of sewage treatment in the South Atlantic Gulf.

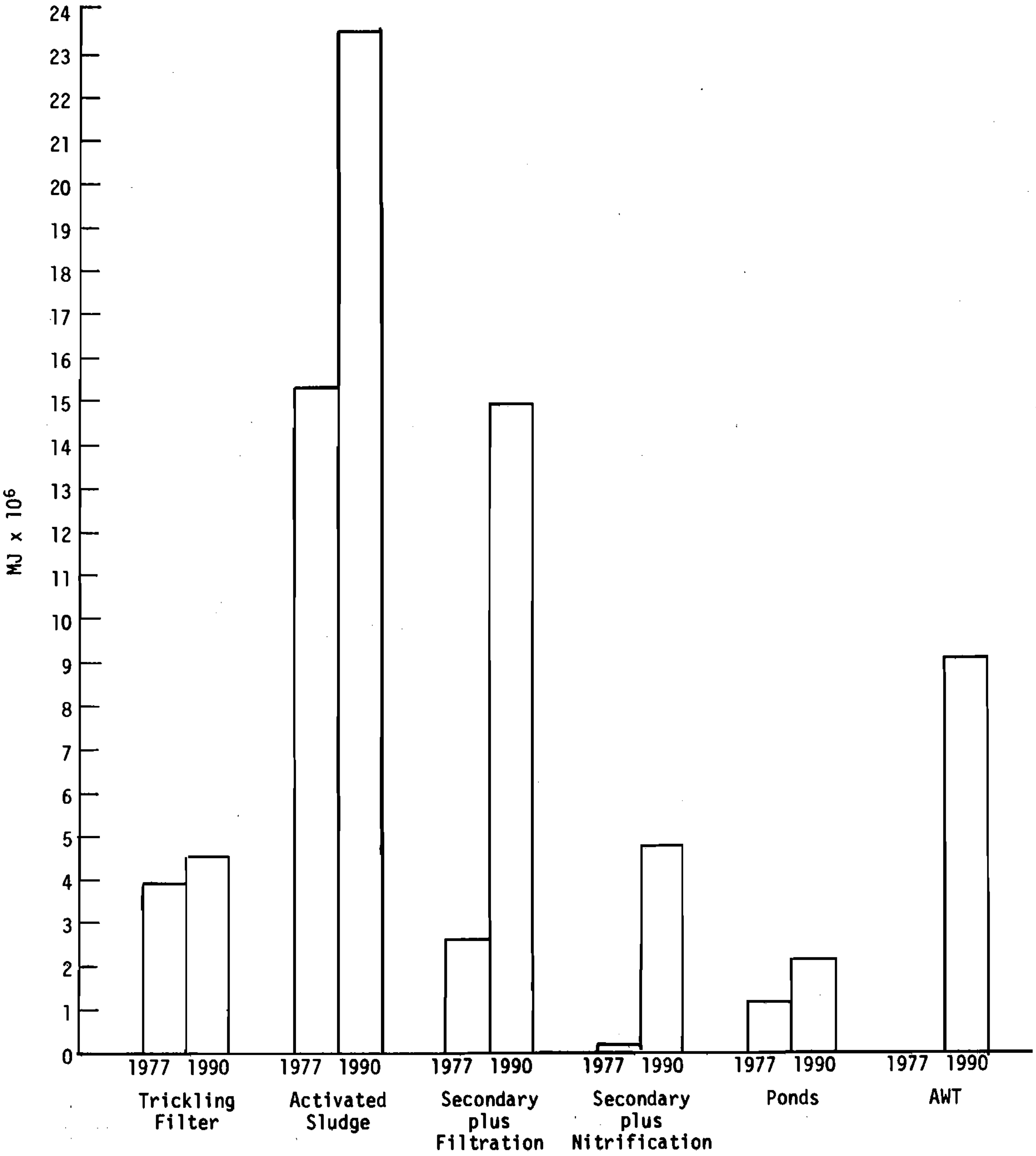


Figure 27. Primary and secondary energy consumption by type of sewage treatment in the Mid-Atlantic and part of the Great Lakes.

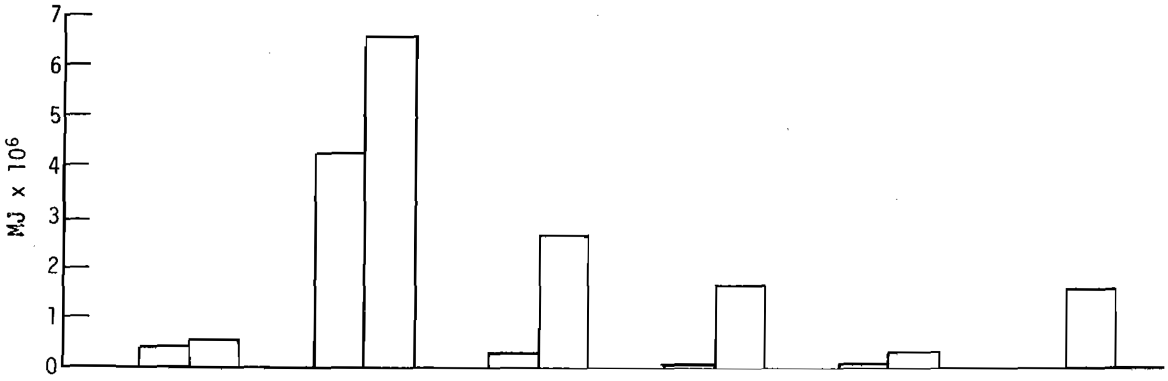


Figure 28. Primary and secondary energy consumption by type of sewage treatment in New England.

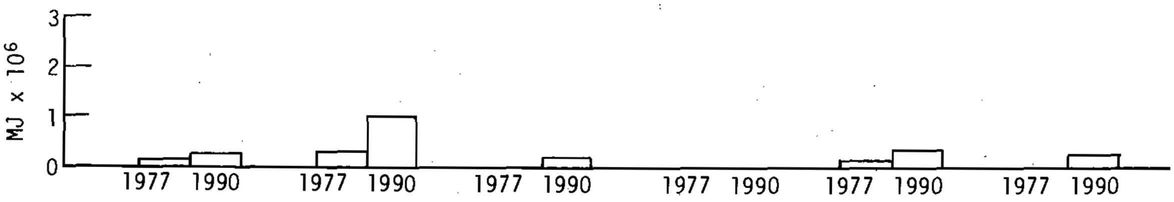


Figure 29. Primary and secondary energy consumption by type of sewage treatment in Alaska and Hawaii.

Focusing on the types of treatment plants themselves, it is apparent that virtually no new trickling filter capacity will be added in the United States. Only California shows a measurable increase in the energy required for trickling filter plants between 1977 and 1990. In many areas, increasing numbers of activated sludge plants will be combined with tertiary units, resulting in a decrease in the energy required for activated sludge plants providing secondary treatment only. The Upper Mississippi is the region in which the greatest decrease in energy for activated sludge plants (secondary treatment only) will occur over the next 12 years. The regions in which the greatest increase in energy for activated sludge (secondary treatment only) is anticipated are the Mid-Atlantic, the Lower Mississippi, and the Pacific Northwest, in descending order of demand. The energy for filtration will increase significantly in all regions of the country between 1977 and 1990. The increase will be the greatest for Ohio and Tennessee, the Mid-Atlantic, and the Upper Mississippi regions. Nitrification will be less commonly introduced between 1977 and 1990 than will filtration because it is a more complex, more energy-intense process. As a result, filtration will be preferred for all cases in which this less costly tertiary process can achieve the desired quality standards. The areas in the country in which energy for nitrification will increase most between 1977 and 1990 are the South Atlantic Region, the Mid-Atlantic Region, and California. Because the location of AWTs estimated to be in operation by 1990 is not given in the USEPA data, they have been apportioned among the 12 geographical regions on the basis of the number of plants greater than 50 mgd that will operate there in 1990. Based on this assumption, it appears that the Mid-Atlantic and Ohio and Tennessee regions will experience the greatest growth in the energy required for AWTs. Table 63 indicates the percentage of the total energy requirement for sewage treatment that is used in each region for all tertiary treatment processes combined.

National Energy Requirements for Sewage Treatment by Treatment Type

The data presented in Table 64 summarize the capacity for the nation as a whole according to type of treatment and the energy needed annually to accomplish each type of treatment. Table 65 indicates the percentage of the total energy required for sewage treatment that is consumed by each category of treatment. In both 1977 and 1990, the largest percentage of energy is required by the activated sludge, secondary treatment process. In 1990, however,

Table 63

Primary and Secondary Energy Required to Accomplish Tertiary Treatment

Region	1977 (MJ x 10^6)	Percent Total Energy	1990 (MJ x 10^6)	Percent Total Energy
Pacific Northwest		8	3600	31
California	988	10	13377	57
Great Basin	138	3	5819	55
Missouri Basin	375	8	1771	24
Askansas-White-Red	699	4	13840	51
Upper Mississippi	1538	6	20040	45
Lower Mississippi	249	3	4648	25
Ohio and Tennessee	1557	10	21706	57
South Atlantic Gulf	2779	13	19374	54
Mid-Atlantic	2828	12	28902	49
New England	427	8	5972	44
Alaska and Hawaii	0	0	253	14
United States	11998	9	139305	48

Table 64

United States
Primary and Secondary Energy and Capacity Summary

Treatment Type	Total Capacity (mgd) 1977	Total Capacity (mgd) 1990	Annual Energy Requirement (MJ x 10^6) 1977	Annual Energy Requirement (MJ x 10^6) 1990
Trickling Filter	6025	6256	27703	28248
Activated Sludge	15343	17189	72518	84656
Secondary & Filtration	1772	14822	9746	81508
Secondary & Nitrification	372	4085	2252	26189
Ponds	7209	11162	27432	40085
AWT	0	3000	0	31608
Total for all treatment types	30722	56514	139651	292295

Table 65

Percentage of Total Primary and Secondary Energy for Sewage Treatment Required by Each Treatment Process in the United States

Treatment Type	Percent 1977	Percent 1990
Trickling Filter	19.8	9.7
Activated Sludge	51.9	29.0
Filtration	7.0	27.9
Nitrification	1.6	8.9
Ponds	19.6	13.7
AWTs	0	10.8

activated sludge for secondary treatment uses a much smaller portion of the total energy than is the case in 1990. In both 1977 and 1990, nitrification requires the smallest percentage of the total energy needs. The histogram of Figure 30 represents the increase in MJ required annually for each treatment type between 1977 and 1990. For the nation as a whole, the increase in the energy required for filtration exceeds that of any other treatment category. Second in magnitude is the growth in energy demanded for operation of AWTs. Of the tertiary treatment categories, the energy required for nitrification will grow least between 1977 and 1990. In the primary and secondary treatment categories, the increase in energy required for activated sludge will be almost the same as the expected increase in the energy required for operation of ponds. Virtually no new trickling filters will be constructed between 1977 and 1990.

Regional Comparisons of the Combined Energy for Sewage Treatment

A comparison of the total energy requirements for sewage treatment throughout the United States in 1977 and 1990 is given on a regional basis in the histogram of Figure 31. This graph is constructed from the energy totals given for each region in Tables 51 through 62. The energy requirements are summed over all treatment types at all capacities for each region considered. Table 66 presents essentially the same data expressed as percentage change in the annual energy requirement between 1977 and 1990. Starting with Alaska and Hawaii, the region with the greatest percentage increase during this time interval, the regions are listed in descending magnitudes of change, finishing with the Missouri Basin, in which the percentage change between 1977 and 1990 in the annual energy required is smallest (64 percent). The large percentage increase in the energy required for sewage treatment in Alaska and Hawaii occurs because it is assumed that an AWT will be built in this region by 1990.

A large percentage change in the energy required between 1977 and 1990 does not necessarily indicate a high or low initial level of energy use for sewage treatment. Alaska and Hawaii, for example, have the highest percentage increase in the energy requirements but consume the smallest amount of energy in 1977 and 1990 of all the regions defined. New England also has relatively small annual energy requirements compared to other regions and a very large percentage change in the energy required by 1990. The Mid-Atlantic and South

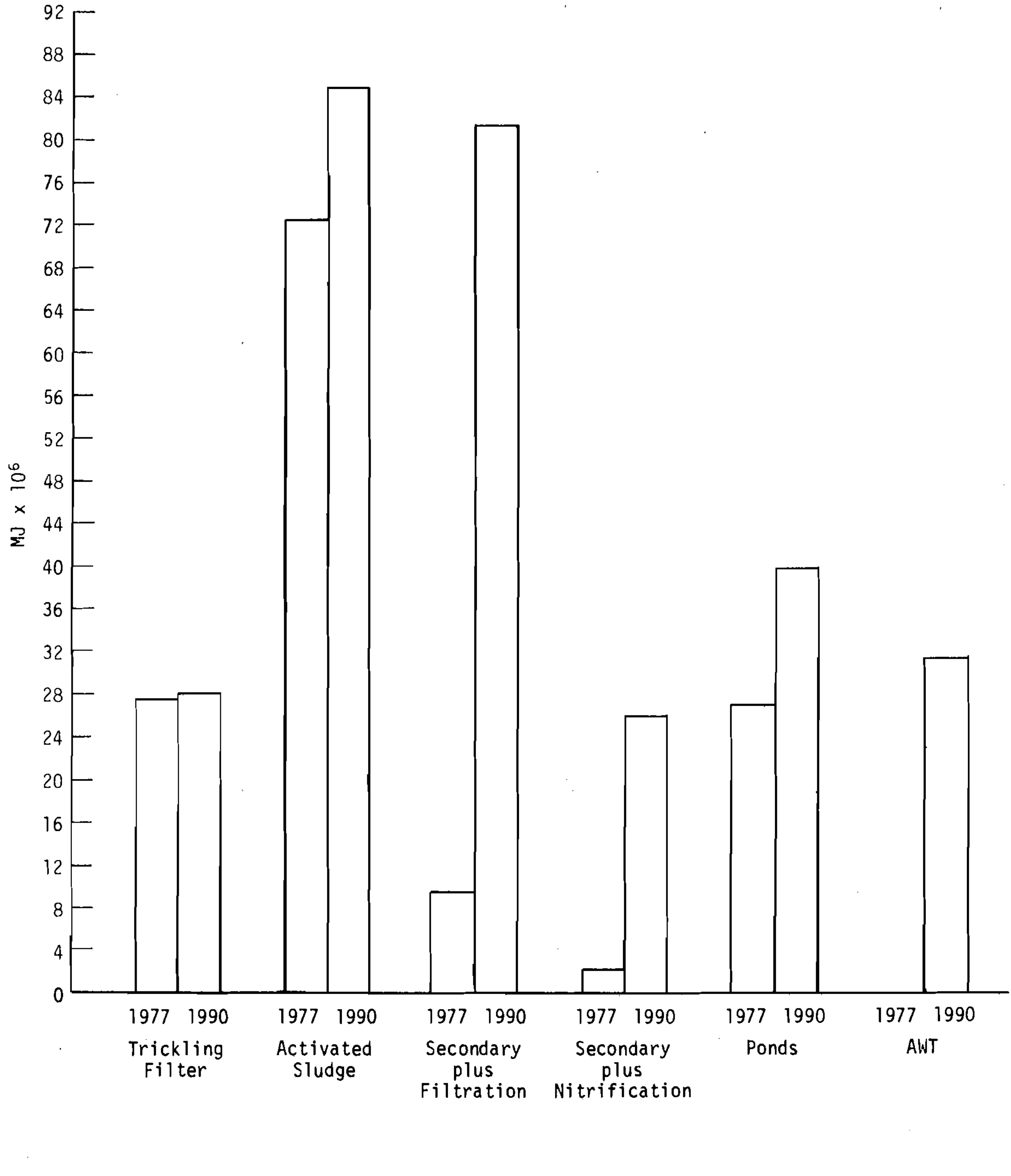


Figure 30. Primary and secondary energy consumption by type of sewage treatment in the United States.

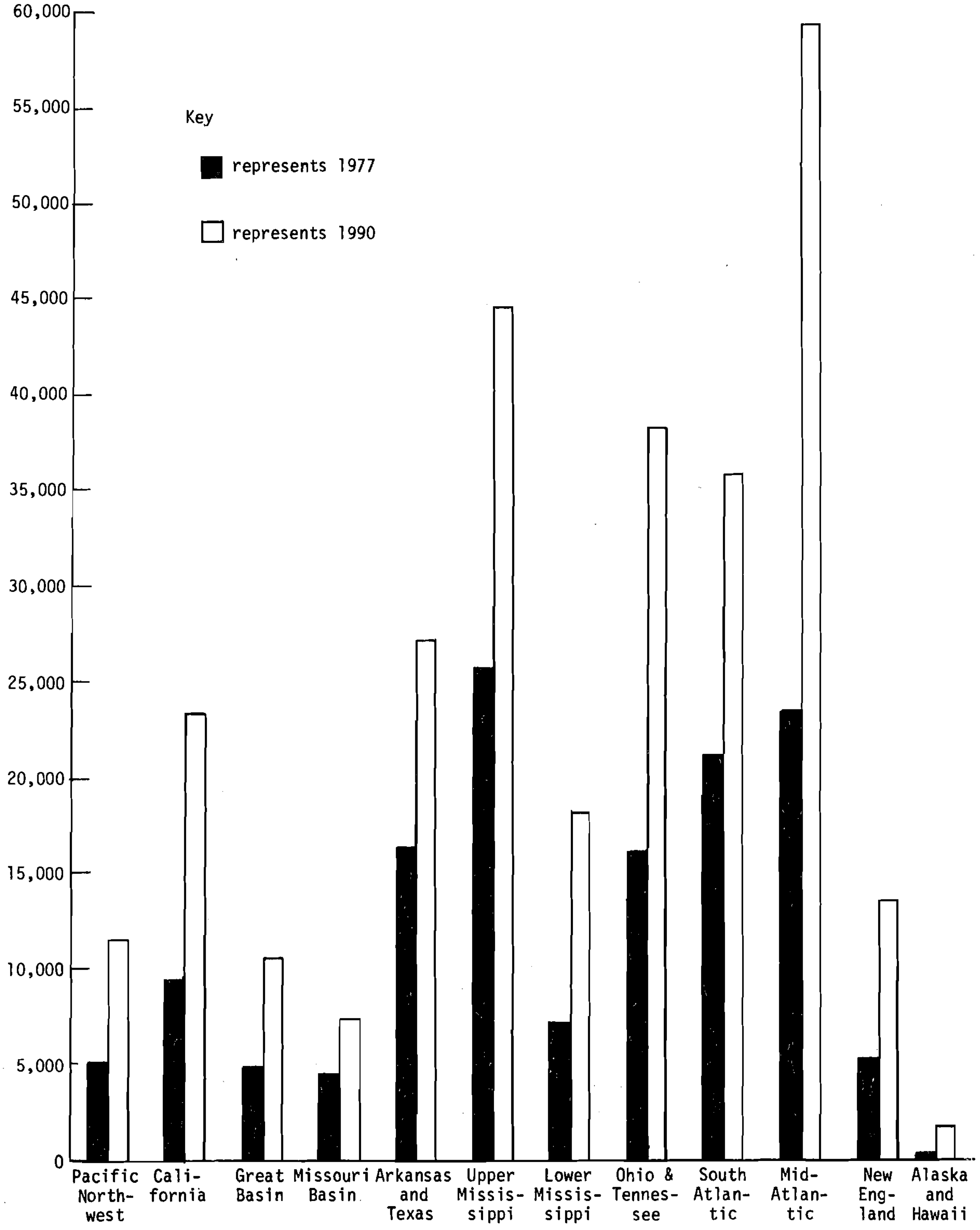


Figure 31. Primary and secondary energy consumption for sewage treatment by geographic region.

Table 66

Percentage Change in the Total Primary and Secondary Energy Required by Regions--1977 and 1990 Compared

Region	Annual Energy Requirement MJ x 10^6 1977	1990	Percent Change over 1977
Alaska & Hawaii	269	1,855	590
Lower Mississippi	7,246	18,285	152
Mid-Atlantic	23,476	59,192	152
New England	5,380	13,511	151
California	9,467	23,433	148
Ohio & Tennessee	16,164	38,335	137
Pacific Northwest	5,029	11,674	132
Great Basin	4,870	10,612	118
Upper Mississippi	25,914	44,710	73
S. Atlantic Gulf	21,018	35,800	70
Arkansas-White-Red	16,259	27,397	69
Missouri Basin	4,558	7,489	64
United States	139,651	292,295	109

Atlantic Gulf have approximately equal annual energy requirements in 1977, yet the percentage increase by 1990 will be 152 percent for the Mid-Atlantic and only 70 percent for the South Atlantic Gulf. Ranked by total energy consumed in 1990, there are five regions with relatively high energy demand: the Mid-Atlantic, Upper Mississippi, Ohio and Tennessee, South Atlantic Gulf, and Arkansas-White-Red Regions. The seven comparatively low-energy-use regions are California, Lower Mississippi, New England, Pacific Northwest, Great Basin, and Missouri Basin, followed by Alaska and Hawaii.

National Energy Requirements for Sewage Treatment in Perspective

As discussed in the introduction, one method of assessing the importance of the change in energy required for sewage treatment is to compare it with the increase in the energy demanded over all consuming sections of the nation. Between 1977 and 1990, the growth rate in national energy consumption as estimated in the *Project Independence* report[4] lies between 30 and 44 percent, depending on whether conditions of energy conservation or conditions of less constrained energy use are assumed. As indicated in Table 66, for the United States as a whole the energy required for sewage treatment is expected to increase 109 percent between 1977 and 1990. This figure is significantly higher than the high growth energy scenario that anticipates a 44 percent increase in national energy consumption during this period. In all but four of the regions considered, the percentage increase in the annual energy requirement of 1990, as compared with that of 1977, is even greater than the 109 percent observed for the nation as a whole. Excluding Alaska and Hawaii, the highest percentage increases in energy required for sewage treatment occur in the eastern half of the country--the Lower Mississippi, Mid-Atlantic, and New England--although California follows close behind. These energy increases are approximately three times higher than increases anticipated for the nation as a whole. At the low end of the scale, regions including the Missouri Basin, Arkansas-White-Red, and South Atlantic Gulf have energy requirements increasing approximately one-and-a-half times faster than the national demand for energy, even without a program of national energy conservation.

Although the rate at which energy is being demanded for sewage treatment is increasing much faster than energy consumption by the nation as a whole, it is important to recognize that a very small percentage of the total national energy requirement is actually consumed in sewage treatment. Table 67 gives three different estimates of the national energy consumption in 1977 and 1990. The energy requirement for sewage treatment as calculated in this study is less than 0.3 percent of the national energy requirement in both 1977 and 1990 under all three estimates of national energy consumption.

Although the impact of conserving energy for sewage treatment will have a relatively small effect on the national requirement for energy, it is still a relevant concern. It is important to recognize that after 1990 the energy requirements for sewage treatment may escalate at an even faster rate as increasingly complex tertiary systems become more widely used. Minimizing the operating costs of sewage treatment facilities and limiting new capital investment will be a matter of extreme importance in most municipalities.

Additional attention should also be given to ways of utilizing the methane gas that is produced in anaerobic digestion of sludge. In many sewage operations

Table 67

Primary and Secondary Energy for Sewage Treatment Compared to Total National Energy Requirement in 1977 and 1990

	Total Energy Use in U. S.	
	1977	1990
1. FEA Energy Projection* Conservation Case	81.11×10^{12} MJ	105.44×10^{12} MJ
2. FEA Energy Projection* No Conservation Case	87.15×10^{12} MJ	125.49×10^{12} MJ
3. EPA Energy Projection+	90.74×10^{12} MJ	120.02×10^{12} MJ

	Total Energy Use for Sewage Treatment	
	1977	1990
EPA draft data from 1976 needs survey	0.14×10^{12} MJ	0.29×10^{12} MJ

	Percent of Total Energy for U.S. Sewage Treatment Rep. under 3 Scenarios of National Energy Growth	
	1977	1990
1. FEA Energy Projection Conservation Case	0.17	0.27
2. FEA Energy Projection No Conservation Case	0.16	0.23
3. EPA Energy Projection	0.15	0.24

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*From Federal Energy Administration, *Project Independence Report*, Nov. 1974.

+From "The Cost of Air and Water Pollution Control - 1976 through 1985," EPA Report to Congress, April 1977 Draft.

presently producing methane gas, this potential energy resource is flared rather than used as fuel in the treatment system. High costs of preparing the gas for use are an important factor, but increasing attention is being given to use of manufactured methane for heating the digesters or for generation of electricity.

The importance of the escalating energy requirements for sewage treatment has already been acknowledged by the USEPA. The agency is presently designing a new set of guidelines to be used by state and federal review boards charged with evaluation of construction grant proposals. Because of the high capital cost of new sewage treatment facilities, most plants are constructed only when federal assistance becomes available. Review boards decide which proposals will receive the first available funds. The new USEPA guidelines will ensure that the energy requirements of treatment are given high priority in evaluation of treatment proposals. Several alternative plans are to be submitted for each new treatment site planned, and the energy requirements both direct (electricity and fossil fuel inputs) and indirect (chemical and other material inputs) must be delineated for all of the alternatives presented. Sensitivity to the energy requirements of sewage treatment is well warranted because the very rapid growth rate in the energy required to operate sewage treatment plants over the next 12 years may well be exceeded in the subsequent decade.

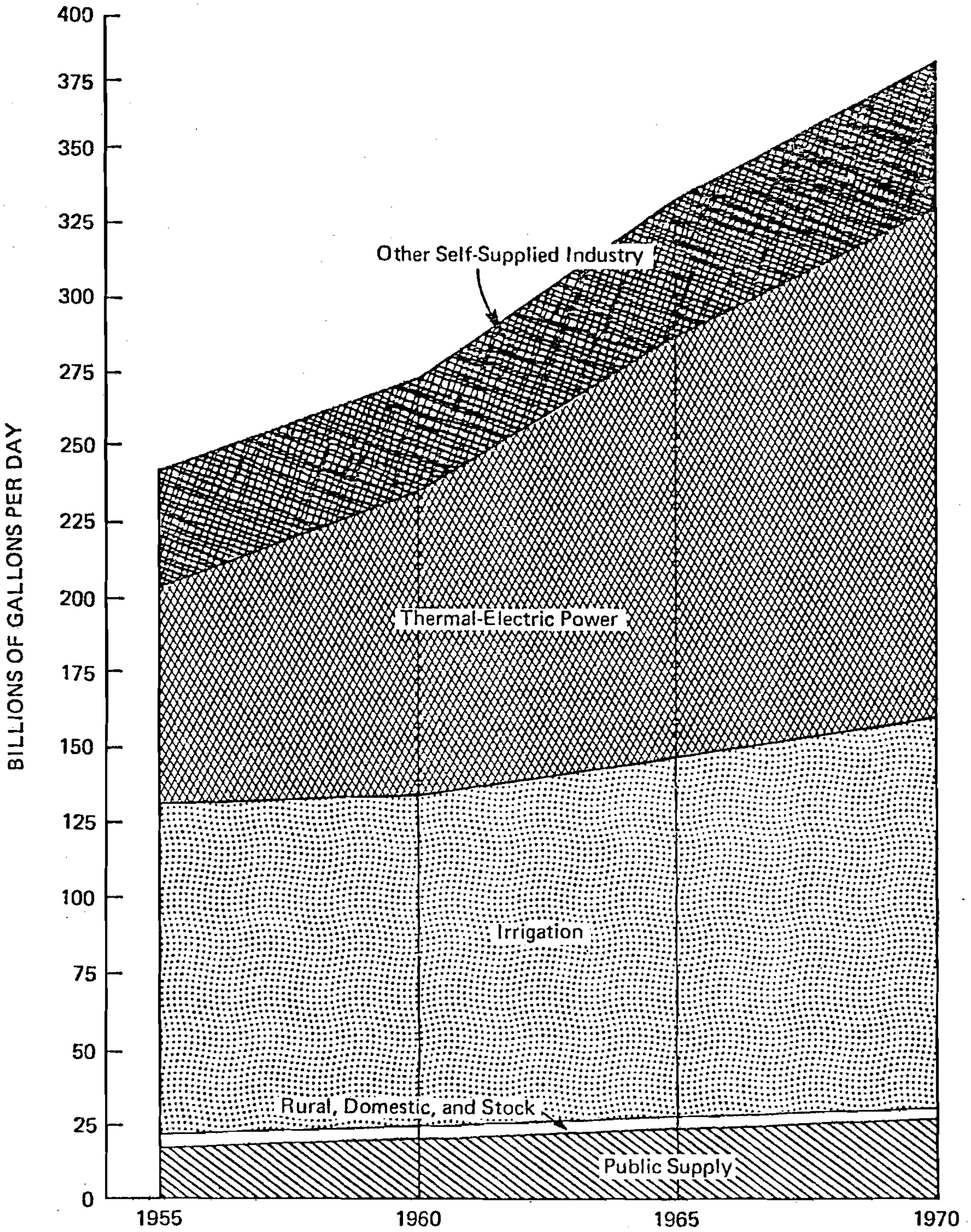
This widely acknowledged growth in the future energy requirements for sewage treatment has prompted many municipal sewage engineers and others to raise the question as to whether water quality is improved sufficiently to justify the high capital investment and increased operating expenses that in general accompany more stringent standards. Many people working in this field think that the public, while desirous of ensuring the stability of aquatic habitats and protecting both recreational areas and drinking supplies from serious, possibly irreversible degradation, has been too zealous. Some observers feel that the public is ignorant of the costs measured in dollars, in energy, and in the materials that many of the new water quality standards impose. It is speculated that there may even be a reversal in public support of water quality when increasing numbers of advanced treatment units are brought on line and when the full cost of imposing stringent standards is borne by the taxpayers. These arguments can only be evaluated by comparing those costs with the total social costs of their alternatives. Resolution of the controversy over the adequacy of past, present, and proposed standards will require a precise accounting of the environmental and social benefits achieved through imposition of stricter standards as well as costs and benefits achieved through imposition of stricter standards as well as costs and benefits of less stringent water quality standards. While many factors enter into issues of environmental regulation, a more precise quantification of the gains in water quality and environmental preservation to be achieved with each increment of energy, material, and dollar inputs added is necessary if a judicious allocation of resources is to be guaranteed.

4 IRRIGATION

Three irrigation projects are examined in this chapter. Because such large quantities of water are necessary for crop production, energy requirements for irrigation are an important part of the comprehensive energy requirement to supply water for various needs. In 1970, 60 percent of fresh water consumed in the United States was used for irrigation. Figures 32 and 33 indicate historic withdrawal and consumption, respectively, of fresh water in the United States.

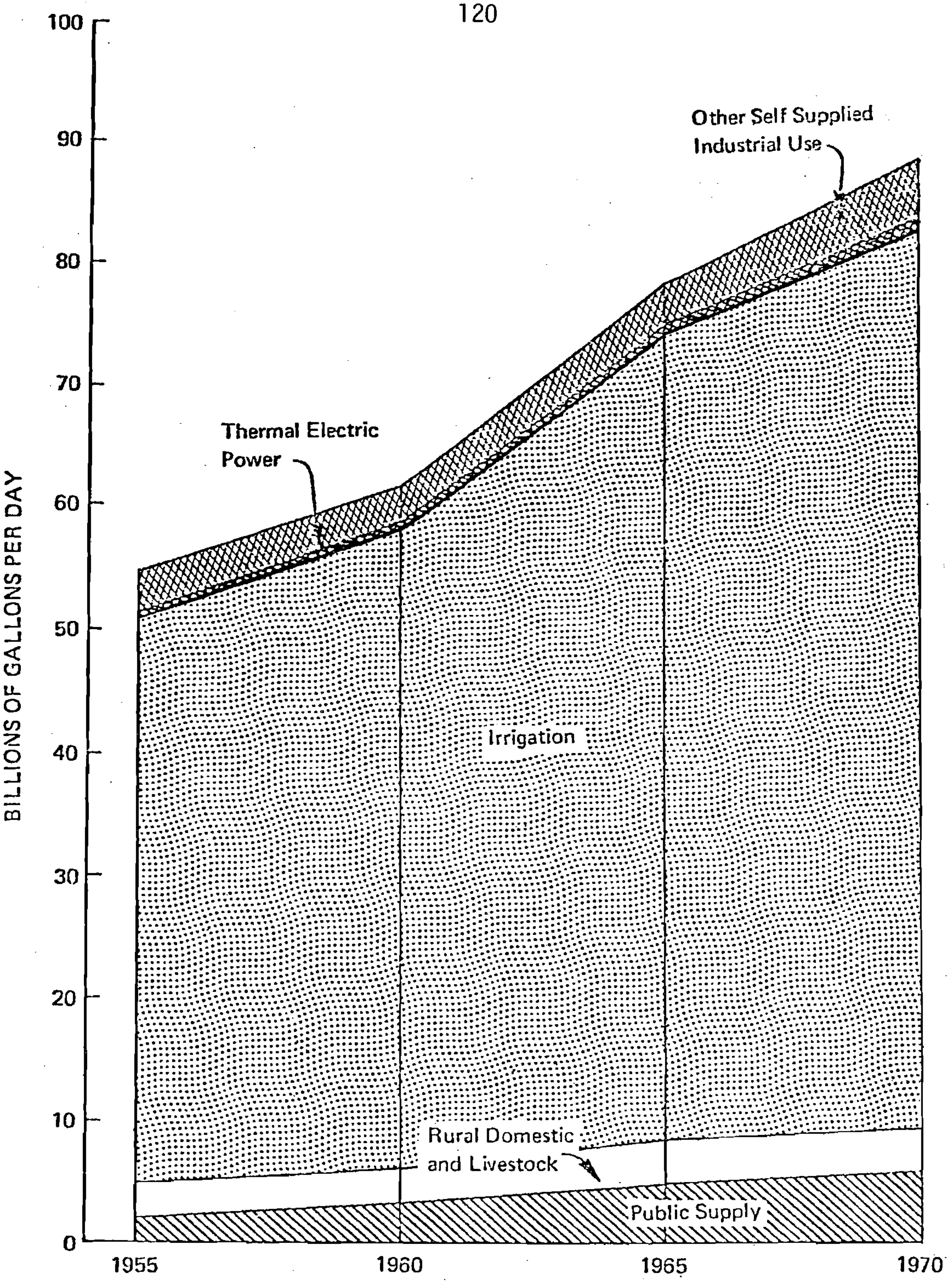
The irrigation projects chosen for this study are located in California, Texas, and Arizona, states that are major irrigators and are supplied by a preponderance of groundwater rather than surface water. The first irrigation area presented is located in California. This state, an important agricultural center for the nation, withdraws more ground- and surface water annually than does any other state in the Union. In 1970, California withdrew 48,000 mgd, or 13 percent of the national withdrawals totalling 370,000 mgd.[5] Second to California was Texas, where 27,000 mgd, or 7 percent of the total national withdrawals, was used. With regard to water specifically for irrigation, California is again far in the lead. Table 68 lists withdrawals of ground- and surface water for use in irrigation in 1970 for the nation as a whole and for the five states that are the major centers of irrigation.

The following discussion of irrigation in Kern County, California, in the High Plains of Texas, and in the San Carlos Project of Arizona is intended to examine a probable pathway that energy requirements for irrigation may take. In each of the irrigation projects discussed, many simplifying assumptions have been made in projecting possible future energy requirements. Average depths to water table and average rates of decline in the water table have been used in all the calculations. These rates are helpful in trying to develop a broad overview of the areas studied, but they mask locally important extremes within an area. Fluctuations in annual rainfall, increases and decreases in the costs of irrigation, changes in the market value of crops, and the availability and quality of surface and groundwater supplies all influence the future of irrigation in these areas. This study does not attempt to anticipate



Source: *Federal Energy Administration Project Independence Blueprint, Final Task Force Report, Water Requirements, Availabilities, Constraints, and Recommended Federal Actions.* Nationwide Perspective, Part II, 1974. Prepared by the Water Resources Council, p. 15.

Figure 32. Historic withdrawal of water for major uses.



Source: *Federal Energy Administration Project Independence Blueprint, Final Task Force Report, Water Requirements, Availabilities, Constraints, and Recommended Federal Actions.* Nationwide Perspective, Part II, 1974. Prepared by the Water Resources Council, p. 16.

Figure 33. Historic consumption of water for major uses.

Table 68

Water Use for Irrigation in 1970

	Groundwater Withdrawn (mgd)	Percent of National Total	Surface Water Withdrawn (mgd)	Percent of National Total	Total Withdrawn (mgd)	Percent of National Total	Total Consumed (mgd)	Percent of National Total
U.S.	45,000	100	81,000	100	126,000	100	73,000	100
California	16,000	36	17,000	21	33,000	26	20,000	27
Texas	7,800	17	2,500	3	10,000	8	81,000	11
Arizona	3,800	8	2,400	3	6,300	5	4,500	6
Idaho	2,100	5	13,000	16	15,000	12	4,700	6
Montana	63	<1	7,600	9	7,600	6	5,400	7

Source: Murray, C. R., and Reeves, E. B. 1972. Circular 676. U.S. Geological Survey.

all these variables in projecting future energy requirements, but instead relies on historic trends, which may not persist into the future. The focus of this report is on the energy required to obtain ground- and surface water supplies from their physical environment. Changes in the energy required to obtain groundwater are calculated from projected declines in the water table. The energy required to obtain surface supplies is based primarily on the energy required to pump this water to areas of irrigation. The energy required to drill wells, to build conveyance systems, and to apply water to the fields has not been included.

Many people connected with the irrigation projects discussed here have shared their expertise, their opinions, and their data in helping to develop the following scenarios. Much of the information they have offered, however, has been carefully qualified as a "best guess" or a "rough approximation" or a "ball park figure." The following calculations, therefore, attempt to capture the *magnitude* of the change in the energy required to obtain water for irrigation. The question asked is not how much energy will be required by a specific project at a specific point in time, but whether irrigation in the United States, particularly in water-short areas of the Southwest, will in the future require a significantly larger portion of domestic energy supplies than they do at present. Should this be the case, a very detailed and precise study of the energy required for acquisition of irrigation water is suggested as an appropriate contribution to an understanding of the energy needs and problems of the future.

Kern County Irrigation Area

Kern County, the first irrigation project considered in this chapter, lies in the San Joaquin Valley, which is part of the Central Valley of California (see Figure 34). The Central Valley encompasses 37.8 percent of the land area in California and receives 47.5 percent of the state's annual runoff of 63 billion gallons daily (1895-1947 average).[6] In addition to the water-short San Joaquin Valley, the Sacramento Valley, an area of water surplus, and the Upper Lake-Kelseyville and Lower Lake-Middletown areas are included in the Central Valley. The San Joaquin Valley has the largest groundwater pumpage of any valley in the United States and has extensive groundwater overdraft, a condition in which withdrawals of water exceed the natural rate of recharge,

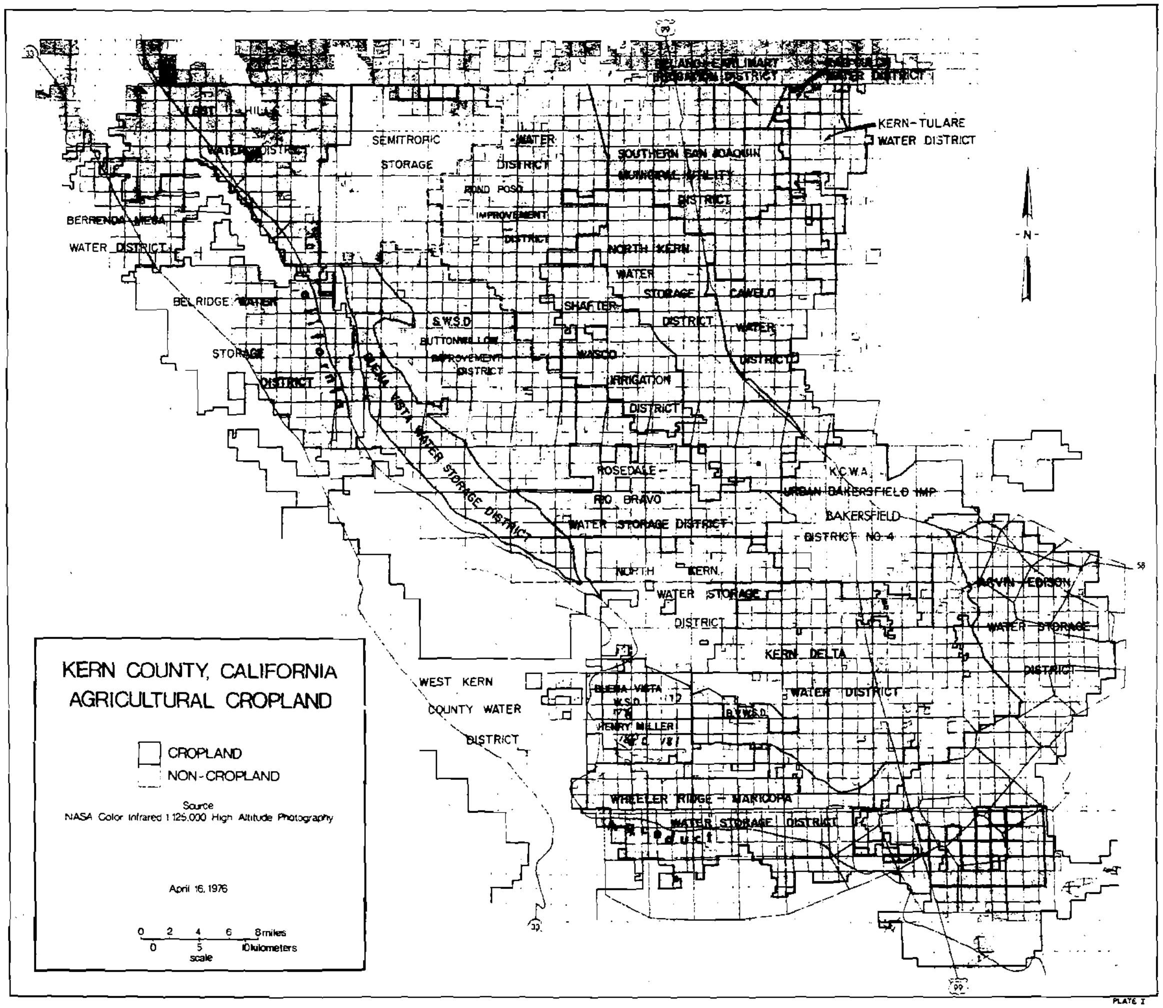


Figure 34. Irrigated acreage in Kern County, California.

resulting in a persistent decline in the water table. Water deficiency in the San Joaquin Valley existed as early as 1921 and provided major incentive for the State Water Plan and the Central Valley Project. The most important cash crops of the area are cotton ($266,741,000 in 1976), grapes ($120,010,000 in 1976), alfalfa hay ($61,305,000 in 1976), and potatoes ($53,924,000 in 1976).[7] Other important crops include citrus fruit, sugar beets, wheat, and grain sorghum.

Approximately three-fourths of the San Joaquin Valley is underlain by groundwater, but only one-third of the land area of Kern County (approximately 3,000 sq mi) is included in this groundwater basin. Groundwater in this area occurs in both confined and unconfined aquifers. The unconfined aquifers lying nearer the land surface provide the more abundant water supply and occur under water-table conditions. The confined aquifers lie 400 to 500 ft beneath the land surface and do not presently supply a significant portion of the groundwater used in the area. The amount of water available in these confined aquifers is undetermined although these reserves are thought to be relatively small.

The energy requirements of supplying water for irrigation presented in this report are based primarily on the energy necessary to pump water from underground storage or to utilize the surface water supplies, which are in large part imported to the area. This study neglects both the energy required for drilling wells (see Appendix II) and the energy consumed in applying water to the land through pressure distribution systems such as sprinkler systems. These additional energy requirements should be roughly similar year to year even though more wells are needed when groundwater in an area approaches depletion and well yields decline. Deletion of these requirements should not significantly influence the magnitude of the change observed in the energy required between 1975 and 2000, although their inclusion is important for an exact and extended study of energy requirements for irrigation.

The energy-use scenario developed here begins with the year 1975. The data presented in Table 69 for the years 1975 to 1977 were provided by the Kern County Water Agency and estimate consumption of ground- and surface water for that period. In 1976 and 1977 severe drought conditions prevailed throughout

Table 69

Water Sources for Irrigation in the Kern County Groundwater Basin Area

Source	1975 mil gal	 % total	1976 mil gal	 % total	1977 mil gal	 % total
Kern River	130,492	11.8	74,714	6.6	49,529	4
California Aqueduct	179,559	16.2	187,595	16.6	57,024	4.9
Friant-Kern Canal	147,866	13.3	73,071	6.4	25,416	2.2
Effective Precipitation	57,024	5.1	28,512	2.5	19,958	1.7
Groundwater Extraction	594,503	53.6	768,129	67.9	1,001,480	86.8
Total Supply	1,109,444	100.0	1,132,021	100.0	1,153,407	100.0

the state of California, and a major increase in the rate of groundwater withdrawals occurred to compensate for reduced surface supplies. Aside from precipitation in the area, surface supplies come from three main sources: the Kern River, the California Aqueduct, and the Friant-Kern Canal. In 1975 each of these sources supplied approximately one-third of the total surface supply. For all years subsequent to 1978 it is assumed that the normal 1975 surface water supplies and precipiation will be available. The winter flood of 1978 is not taken into account in this study, so the projected use of groundwater through the end of the century may be an upper bound if no serious droughts occur in the next 20 to 30 years. Inevitably any projection of the energy requirements for irrigation incorporates assumptions about weather patterns, economic conditions, and agricultural practices, any of which may quickly change, seriously compromising trend line projections. The numbers presented in these energy calculations therefore are intended to suggest a probable evolution of energy requirements should historic tendences persist. They should not be treated as literal quantitative predictions of the energy requirements.

In all but extreme weather situations the amount of surface water available to Kern County annually (not including precipitation) is a maximum of approximately 652 x 10^3 mil gal.[8] The surface water supply of 514,941 mil gal (including precipitation) provided in the "normal" year of 1975 is treated as the fixed surface water supply for all years after 1978 and any additional water requirements are met with groundwater. This assumed surface water supply is about 21 percent less than the approximate maximum surface supply available to the area (excluding precipitation). Consequently, the percentage of total supply obtained from groundwater tends to be an upper estimate in projected years. The energy required to deliver surface supplies is based on a very rough estimate provided by the Kern County Water Agency of the requirements of the electrical pumping system. The primary energy required to pump water to Kern County from the Friant-Kern Canal and from the California Aqueduct is estimated at 19,264 MJ/mil gal.* Distribution within Kern County requires an additional 10,910 MJ/mil gal and excludes the energy needed to apply water to the fields. The energy requirement assigned to each of these surface water sources is presented in Table 70, and the energy requirement for surface supplies is assumed to be invariant from 1978 to 2000.

For each year of this study an estimate of the energy needed to obtain groundwater for irrigation is based on a correlation of groundwater withdrawals, depth to water table, and average pumping efficiency. Energy requirements for pumping are determined from Figure 35, provided by the Kern County Water Agency. Characteristic of Kern County is an electrical pumping system with an average efficiency of 60 percent. This efficiency represents a primary energy requirement of 1.75 kwh's to lift one acre ft of water one ft, which is equivalent to an energy requirement of 59.6 MJ needed to lift one mil gal one ft in height. This energy requirement for groundwater pumping is used for all years considered in this Kern County study.

The present (1977) average depth to groundwater (182.5 ft) is calculated from a contour map prepared by the Kern County Water Agency and reproduced in Figure 36. This depth, however, is the static water level and does not accurately

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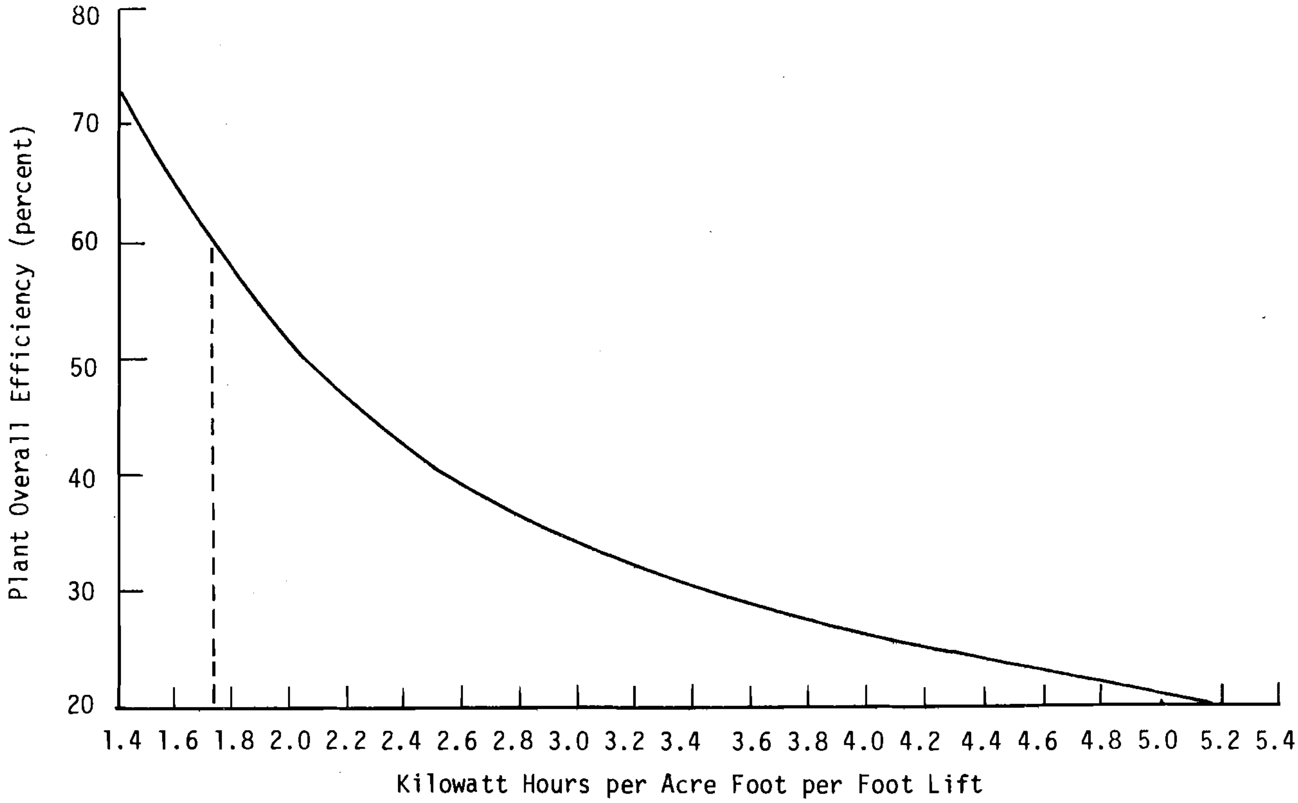
*Just prior to publication of this report, a Kern County official informed the authors that this statement is in error. The Friant-Kern Canal is gravity fed and does not require pumping energy of 19,264 MJ/mil gal. The surface energy requirement presented is therefore higher than it should be. However, because the water supplied by the Friant-Kern Canal is a small part of the total water requirement, correction of the energy requirement for surface water will decrease only slightly the total energy requirement.



Graph provided courtesy of Kern County Water Agency.

Figure 35. Relationship between overall plant efficiency and kilowatt hours per acre foot per foot lift.

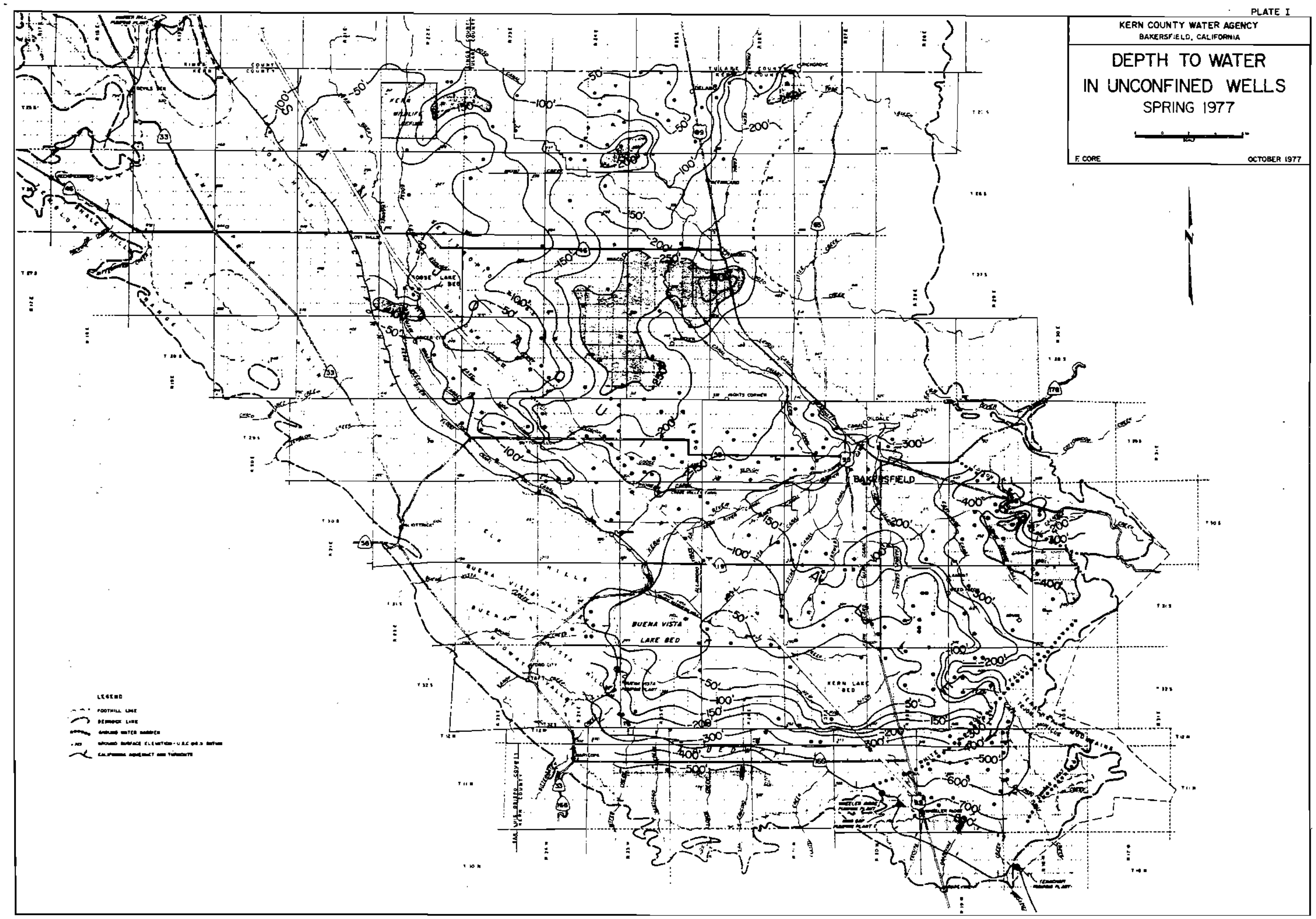


Figure 36. Water level contours in Kern County.

Table 70

Kern County Irrigation Primary Energy Requirements for Surface Water

	mil gal	MJ/mil gal	Total Energy MJ x 10^6
1975			
Kern River	130,492	10,910	1,424
California Aqueduct	179,559	30,174	5,418
Friant-Kern Canal	147,866	30,174	4,462
Precipitation	57,024	0	0
Total surface water	514,941	21,952	11,304
1976			
Kern River	74,714	10,910	815
California Aqueduct	187,595	30,174	5,660
Friant-Kern Canal	73,071	30,174	2,205
Precipitation	28,512	0	0
Total surface water	363,892	23,853	8,680
1977			
Kern River	49,529	10,910	540
California Aqueduct	57,024	30,174	1,721
Friant-Kern Canal	25,416	30,174	767
Precipiation	19,958	0	0
Total surface water	151,927	19,931	3,028

represent the depth to water during the irrigation season.* Because wells are pervasive throughout the area, a "cone of depression" or drawdown of approximately 100 ft occurs when all wells are simultaneously in operation during the planting seasons. Therefore the depth to water for 1977 is calculated at 282.5 ft rather than at the static level of 182.5 ft. The average annual decline in the water table between 1965 and 1975 is approximately 2.3 ft.[9] When the more drastic declines of the drought years (1976 and 1977) are estimated and included, the average becomes a 3.8 ft annual decline for the years 1965 to 1977. For the years 1978 to 1992 (a period of agricultural expansion), depth to water table is estimated using an annual decline of 3.8 ft. After 1993, however, the demand for water is relatively stable, and a more moderate decline

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*Depth to water table in Kern County is approximated by averaging very deep water tables with moderately deep and very shallow water tables existing throughout the county. As a result, this "average" depth may not actually exist at any specific location but affords a measure of water table depth that can be applied to the county as a whole.

of 2.3 ft annually is used in the water table calculation between 1993 and 2000, inclusive. The estimated decline in the water table is presented graphically in Figure 37.

Groundwater withdrawals are most easily examined in four distinct time periods: 1975 to 1977, 1978 to 1988, 1989 to 1992, and 1993 to 2000. For the years 1975 to 1977, data were provided by the Kern County Water Agency and were presented in Table 69. For all subsequent years, projections have been made based on additional information also provided by the Kern County Water Agency. Kern County planners estimate that in each of the years between 1979 and 1988 inclusive approximately 20,000 acres will be added to agricultural production if historic trends persist. Each acre represents, conservatively, an annual water requirement of 1.22 mil gal, which represents a total increase in the groundwater requirement of 24,374 mil gal in each of these years. After 1989, virtually all of the choice land will have been drawn into production, and in subsequent years agricultural expansion is expected to come primarily from double cropping rather than from irrigating less fertile acreage. Double cropping is accomplished either by planting a second crop between the rows of the first crop or, more commonly, by harvesting one crop and then planting a second winter season crop. In both cases, the water requirement for double cropping is approximately 1.5 times the requirement for single cropping, or 1.83 mil gal/acre. In each of the years between 1989 and 1992 inclusively, it is estimated that double cropping will begin on 40,000 of the acres under irrigation. Under this assumption, by 1992, 200,000 acres will be double cropped, and at present crop prices this acreage is the maximum likely to sustain double cropping. After 1992, then, a steady-state condition is anticipated in which the annual water requirement of 1992 (1,543,387 mil gal) is assumed to be very similar to the requirement in the succeeding years projected. After 1992, the water table is expected to continue its decline, as withdrawals will exceed recharge, but it should decline at a slower rate, approximately 2.3 ft annually instead of the 3.8 ft decline which characterizes earlier years. Projected and historic water use for the years 1975 to 2000, as well as estimated depth to water table, is presented in Table 71. Water withdrawals are presented graphically in Figure 38.

In the projections of Table 71, one other geological condition is taken into account, that of the groundwater quality. According to a study by M. R.

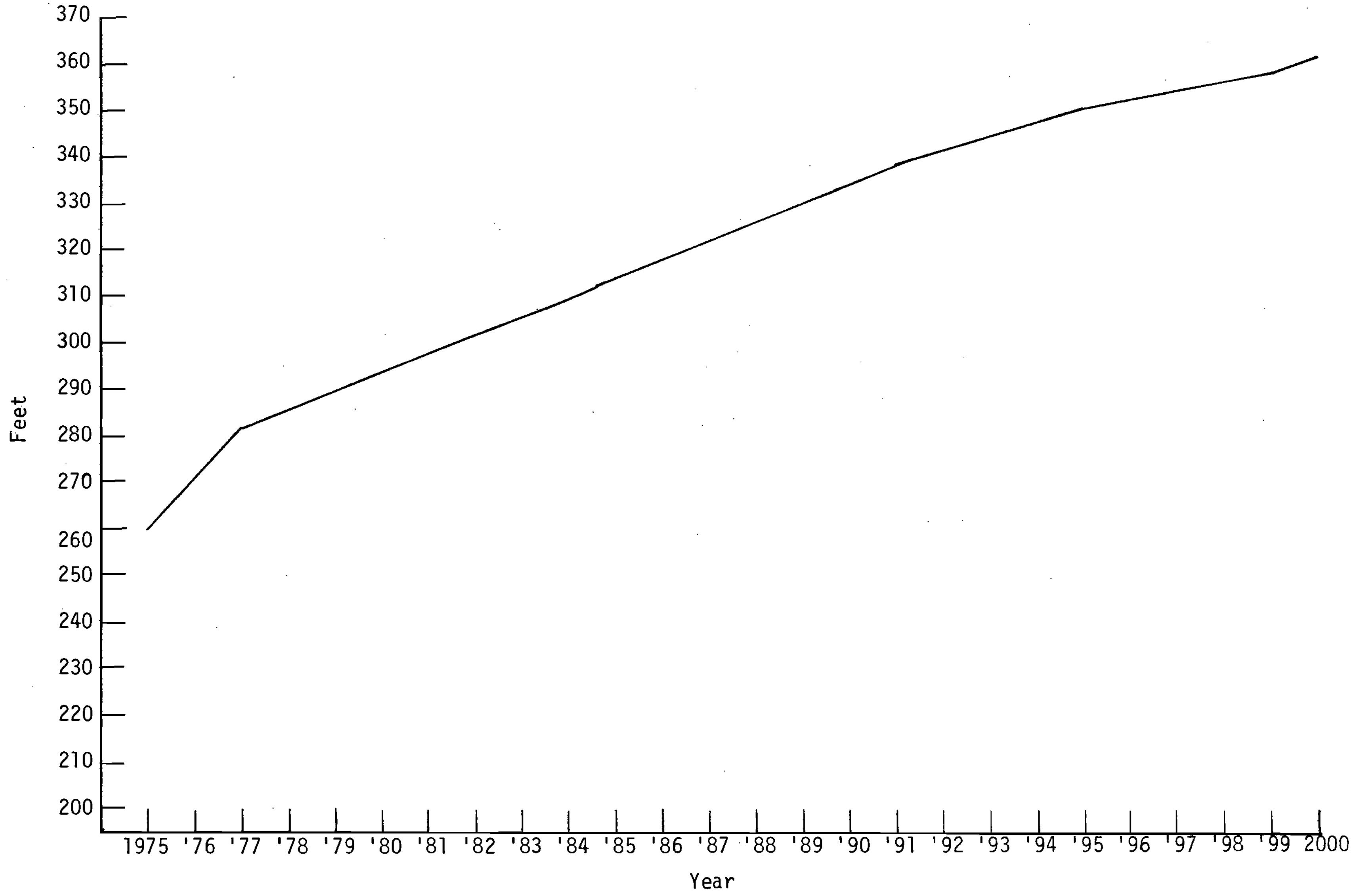


Figure 37. Estimated depth to groundwater in Kern County.

Table 71

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
<u>1975</u>						
surface water	514941		54	259.6	11304	21952
groundwater	594503				9198	15472
total water	1109444				20502	18479
<u>1976</u>						
surface water	363892	-151049	68	269.6	8680	23853
groundwater	768129	+173626			12342	16068
total water	1132021	+ 22577			21024	18572
<u>1977</u>						
surface water	151927	-211965	87	282.2	3028	19931
groundwater	1001480	+243351			16844	16819
total water	1153407	+ 21836			19872	17229
<u>1978</u>						
surface water	259112	+113701	78	286.0	5688	21952
groundwater	918670	- 82810			15659	17045
total water	1177782	+ 20891			21347	18125
<u>1979</u>						
surface water	514941	+255829	57	289.8	11304	21952
groundwater	687214	-231456			11870	17272
total water	1202155	+ 24373			23174	19277

Table 71--*continued*

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
1980						
surface water	514941				11304	21952
groundwater	711588	+ 24374	58	293.6	12452	17498
total water	1226529	+ 24374			23756	19368
1981						
surface water	514941				11304	21952
groundwater	735962	+ 24374	59	297.4	13045	17725
total water	1250903	+ 24374			24349	19501
1982						
surface water	514941				11304	21952
groundwater	760335	+ 24374	60	301.2	13649	17951
total water	1275276	+ 24374			24953	19567
1983						
surface water	514941				11304	21952
groundwater	784709	+ 24374	60	305	14264	18178
total water	1299650	+ 24374			25568	19673
1984						
surface water	514941				11304	21952
groundwater	809083	+ 24374	61	308.8	14891	18404
total water	1324024	+ 24374			26195	19784

Table 71--*continued*

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
1985						
surface water	514941				11304	21952
confined ground-	9749			450	261	26820
unconfined ground-	823707			312.6	15346	18361
total groundwater	833456	+ 24374	62	314.2	15607	18726
total water	1348397	+ 24374			26911	19958
1986						
surface water	514941				11304	21952
confined ground-	9749			450	261	26820
unconfined ground-	848081			316.4	15993	18857
total groundwater	857830	+ 24374	62	317.9	16254	18948
total water	1372771	+ 24374			27558	20075
1987						
surface water	514941				11304	21952
confined ground-	9749			450	261	26820
unconfined ground-	872454			320.2	16650	19084
total groundwater	882203	+ 24374	63	321.7	16911	19169
total water	1397144	+ 24374			28215	20195
1988						
surface water	514941				11304	21952
confined ground-	9749			450	261	26820
unconfined ground-	896828			324	17318	19310
total groundwater	906577	+ 24374	64	325.3	17579	19391
total water	1421518	+ 24374			28883	20318

Table 71--*continued*

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
1989						
surface water	514941				11304	21952
confined ground-	9749			450	261	26820
unconfined ground-	921202			327.8	17997	19537
total groundwater	930951	+ 24374	64	329.1	18258	19612
total water	1445892	+ 24374			29562	20446
1990						
surface water	514941				11304	21952
confined ground-	19499			450	523	26820
unconfined ground-	935826			331.6	18495	19763
total groundwater	955325	+ 24374	65	334.0	19018	19907
total water	1470265	+ 24374			30322	20623
1991						
surface water	514941				11304	21952
confined ground-	19499			450	523	26820
unconfined ground-	960199			335.4	19194	19990
total groundwater	979698	+ 24374	66	337.6	19717	20126
total water	1494639	+ 24374			31021	20755
1992						
surface water	514941				11304	21952
confined ground-	19499			450	523	26820
unconfined ground-	984573			339.2	19904	20216
total groundwater	1004072	+ 24374	66	341.3	20427	20344
total water	1519013	+ 24374			31731	20889

Table 71--*continued*

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
1993						
surface water	514941				11304	21952
confined ground-	19499			450	523	26820
unconfined ground-	1008947			343	20626	20443
total groundwater	1028446	+ 0	67	345.0	21149	20564
total water	1543386	+ 0			32453	21027
1994						
surface water	514941				11304	21952
confined ground-	19499			450	523	26820
unconfined ground-	1008947			345.3	20764	20580
total groundwater	1028446	+ 0	67	347.2	21287	20698
total water	1543387	+ 0			32591	21116
1995						
surface water	514941				11304	21952
confined ground-	29248			450	784	26820
unconfined ground-	999198			347.6	20700	20717
total groundwater	1028446	+ 0	67	350.5	21484	20890
total water	1543387	+ 0			32788	21244
1996						
surface water	514941				11304	21952
confined ground-	29248			450	784	26820
unconfined ground-	999198			350	20843	20860
total groundwater	1028446	+ 0	67	352.8	21627	21029
total water	1543387	+ 0			32931	21337

Table 71--*continued*

Kern County Irrigation
Primary Energy Requirements to Obtain Water

Year	Withdrawals mil gal	Decrease or Increase over Previous Year mil gal	Percent Ground-water	Avg. Depth to Ground-water (ft)	Total Energy to Obtain Water MJ x 10^6	MJ/mil gal to Obtain Water
1997						
surface water	514941				11304	21952
confined ground-	29248			450	784	26820
unconfined ground-	999198			352.2	20947	20991
total groundwater	1028446	+ 0	67	355.0	21758	21156
total water	1543387	+ 0			33062	21422
1998						
surface water	514941				11304	21952
confined ground-	29248			450	784	26820
unconfined ground-	999198			354.5	21111	21128
total groundwater	1028446	+ 0	67	357.2	21895	21289
total water	1543387	+ 0			33199	21510
1999						
surface water	514941				11304	21952
confined ground-	29248			450	784	26820
unconfined ground-	999198			356.8	21248	21265
total groundwater	1028446	+ 0	67	359.4	22032	21423
total water	1543387	+ 0			33336	21599
2000						
surface water	514941				11304	21952
confined ground-	38998			450	1046	26820
unconfined ground-	989448			359.1	21176	21402
total groundwater	1028446	+ 0	67	362.5	22222	21607
total water	1543387	+ 0			33526	21722

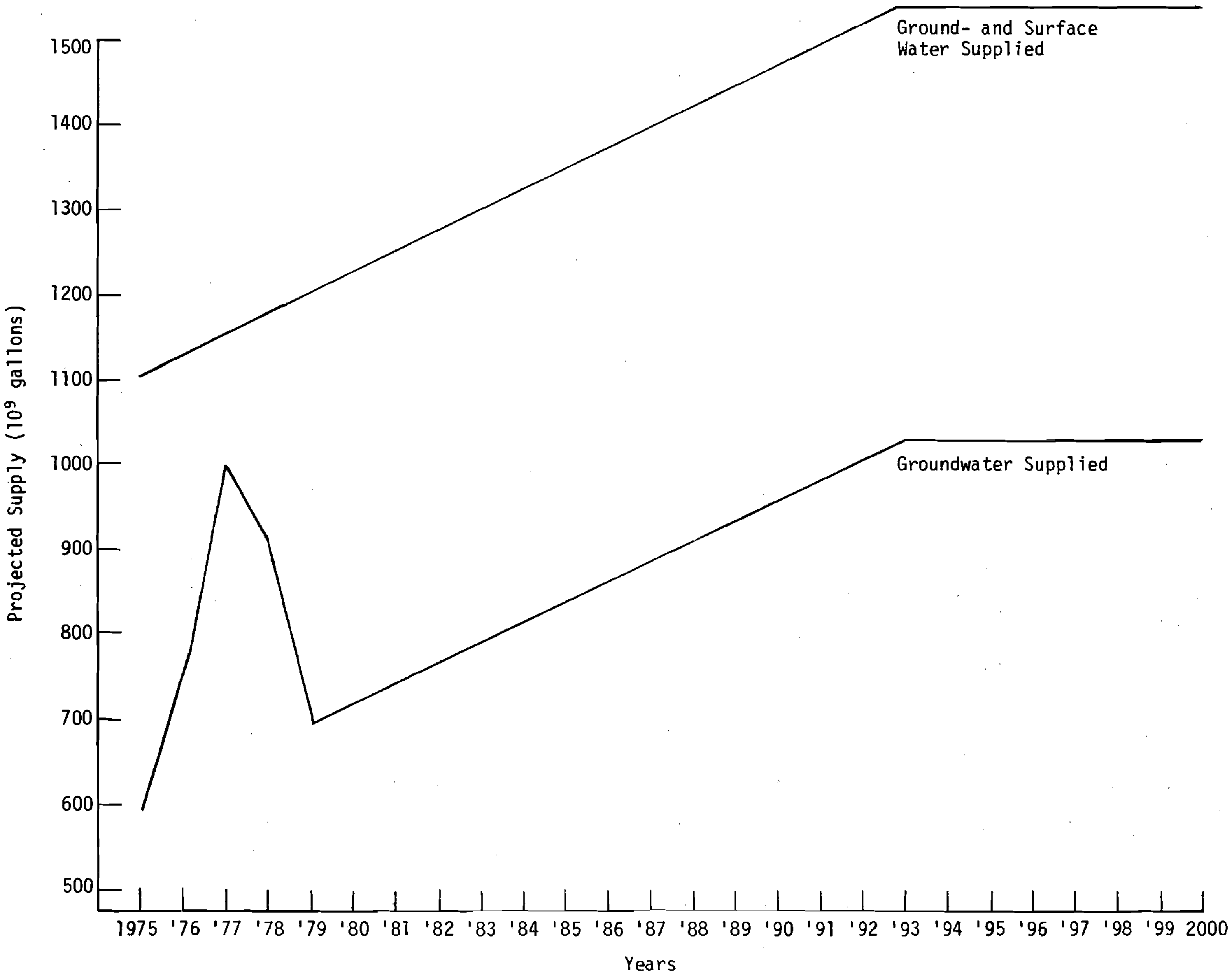


Figure 38. Projected water supplies for Kern County irrigation.

Rector,[10] approximately 32,000 acres in the groundwater basin area will have underlying groundwater of excessive salinity defined as water that measures greater than 3000 micromhos of electrical conductance. Once the unconfined groundwater becomes too saline for irrigation, the farmer must drill the additional footage to the deeper confined aquifer or choose instead to withdraw fields from production. The farmer's decision will depend both on the market value of the crop and on the quantity of water available in the confined reservoir. Beginning with the year 1985, when the first water supplies reach excessive salinity, it is assumed that in all cases the farmer chooses to drill the additional footage to reach the confined aquifer. These confined aquifer sources are estimated to lie at an average depth of 450 ft and are gradually phased in with the addition of 9,749 mil gal of confined groundwater every five years between 1985 and 2000, inclusive.

To calculate the energy required for groundwater withdrawals, the quantity of water withdrawn is multiplied by the depth to groundwater and then by the primary energy required to lift each mil gal one foot. As discussed earlier, calculation of the energy required to obtain surface supplies is found in Table 70. Table 71 presents combined surface and groundwater data for the years 1975 to 2000. Indicated in the table are water withdrawals and the primary energy required to obtain surface, ground-, and combined water supplies in each year. Also calculated is the primary energy required per mil gal of surface, ground-, and combined water supplies. These results are depicted in Figures 39, 40, and 41. In Kern County, water for irrigation is supplied by electrical pumping units. The primary energy requirement for pumping has been calculated using a conversion factor of 11.11 MJ/kwh. The direct energy requirement for supplying water can be calculated using a conversion factor of 3.6 MJ/kwh, which represents only the usable energy of each kwh and excludes energy inputs for electrical generation and transmission. At 60 percent efficiency, the direct energy required to lift one million gallons one foot requires approximately 19 MJ. Table 72 presents the percentage change in water withdrawn and energy required between 1975 and 2000. The total energy required to pump groundwater shows the greatest increase (142 percent) over this period. Because the energy requirement for surface supplies is assumed fixed for all years after 1978, the percentage change in the total energy required for combined supplies is considerably less (63 percent) than that observed for groundwater. The 40 percent increase in the energy required per mil gal of

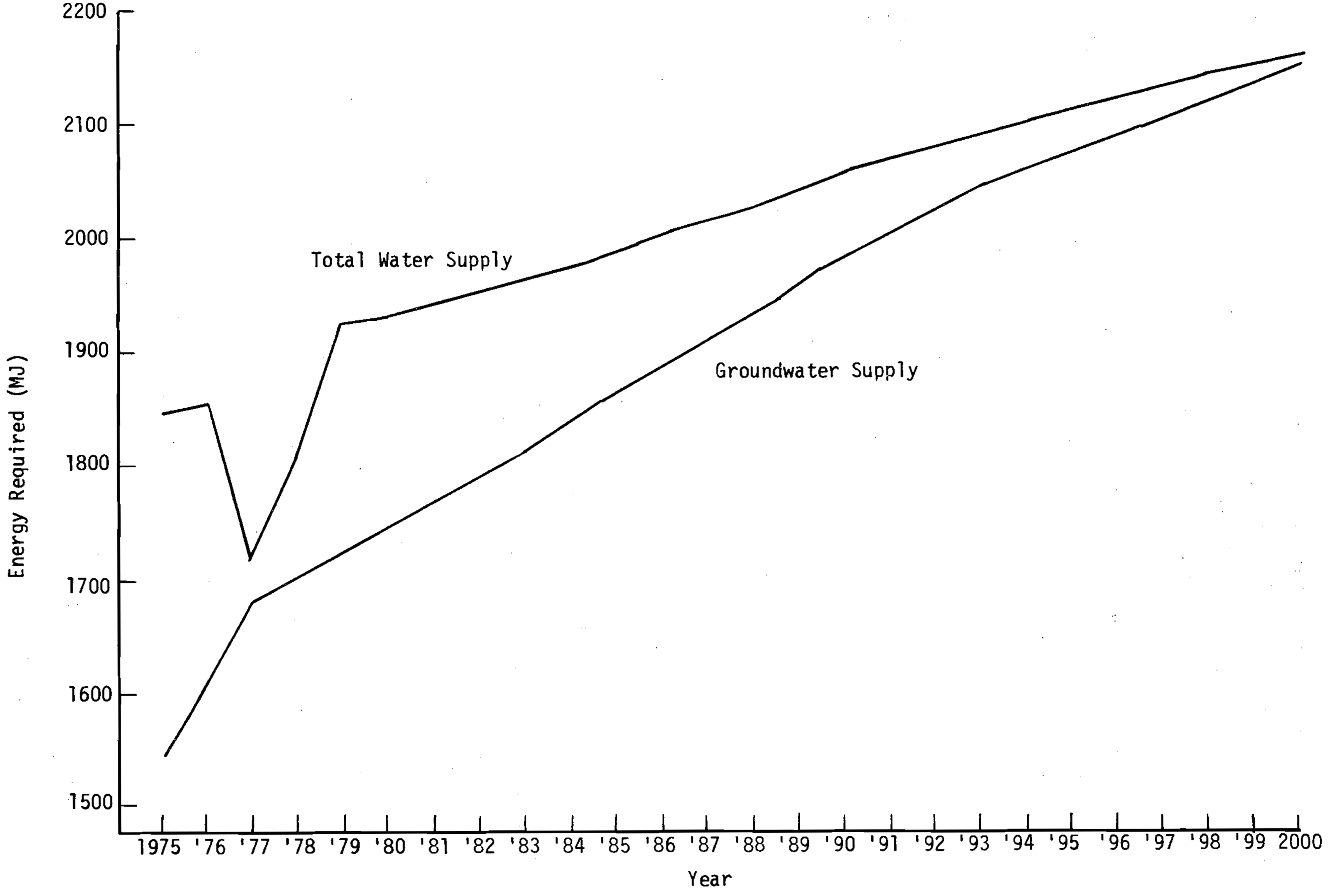


Figure 39. Primary energy required to obtain water for irrigation in Kern County.

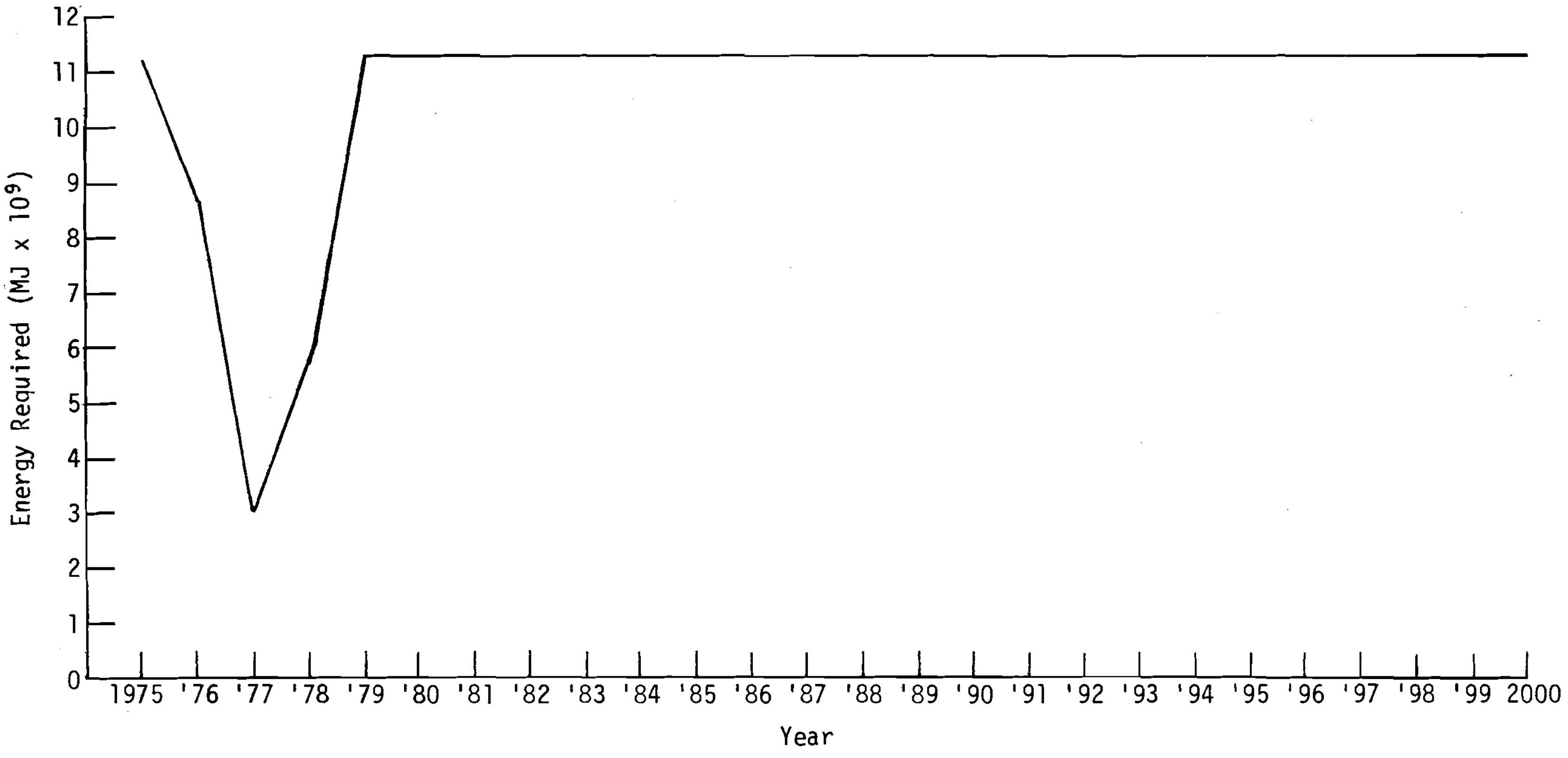


Figure 40. Total primary energy required to obtain surface water for irrigation in Kern County.

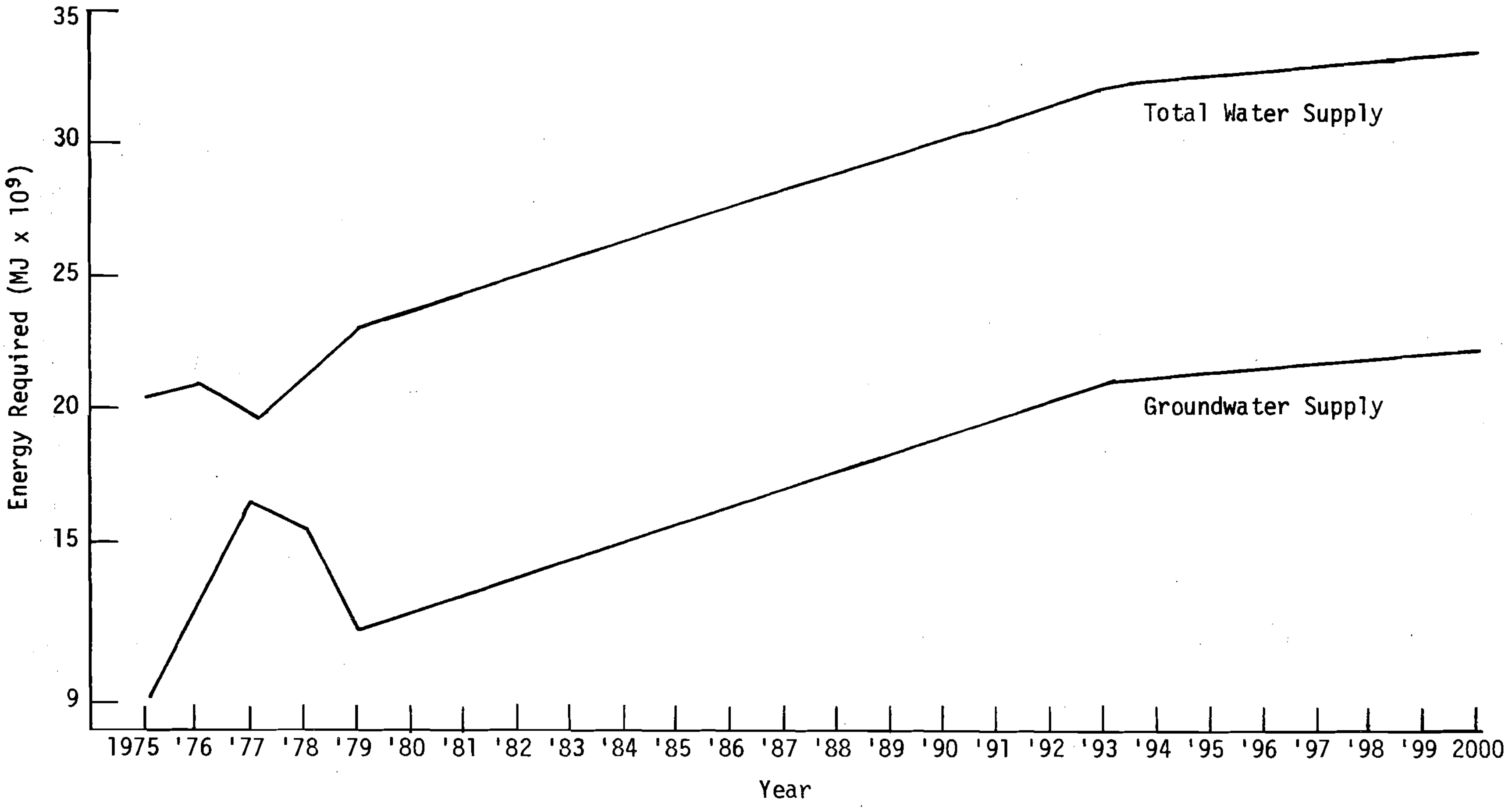


Figure 41. Total primary energy required to obtain water for irrigation in Kern County.

Table 72

Kern County Irrigation Changes in Water and Primary Energy Consumption

	1975	2000	Increase 1975-2000
Water Use			
Surface water used (mil gal)	514,941	514,941	0%
Groundwater used (mil gal)	594,503	1,028,446	73%
Combined supply used (mil gal)	1,109,444	1,543,387	39%
Average depth to water (ft)	259.6	362.5	40%
Energy Use			
Surface water (MJ x 10^6)	11,304	11,304	0%
Groundwater (MJ x 10^6)	9,198	22,222	142%
Combined supply (MJ x 10^6)	20,502	33,526	63%
Surface water (MJ/mil gal)	21,952	21,952	0%
Groundwater (MJ/mil gal)	15,472	21,607	40%
Combined supply (MJ/mil gal)	18,479	21,722	17%

groundwater obtained in 2000 as compared with 1975 corresponds to the 40 percent increase in groundwater depth. The increase in the energy required per mil gal for the combined supply, however, is a more moderate 17 percent.

After the year 2000 it is difficult to project the energy requirement for irrigation. Each unit of water withdrawn from ground storage will require a greater amount of energy unless agriculture in the area is significantly curtailed, allowing the water table to recharge. In some areas, the unconfined groundwater will be entirely depleted after 2000, while in other areas salinity problems will make this source unusable.

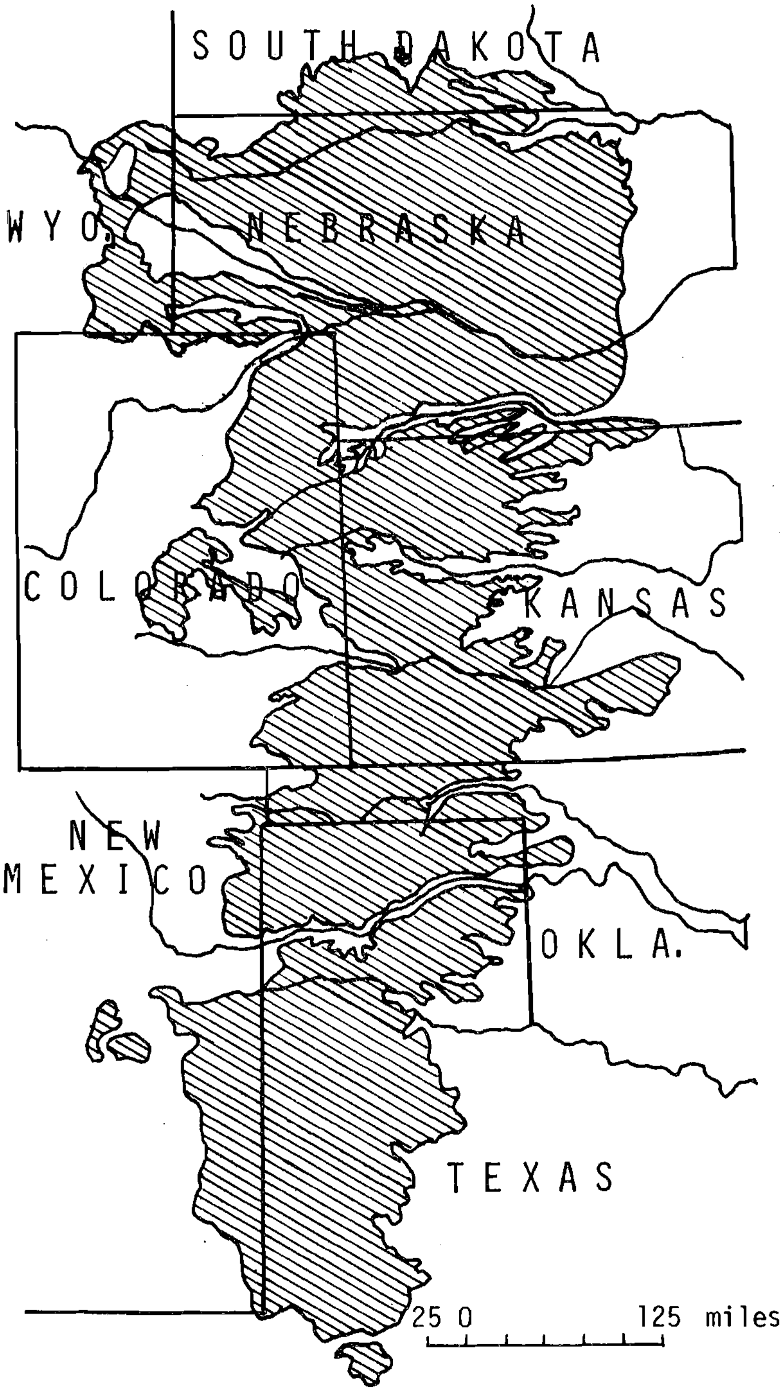
Water scarcity in this area may be met with any of several strategies. At present, the most remote possibility is procurement of additional water supplies through desalination or importation of other outside water sources. Without imported water, some of the Kern County acreage will probably be removed from agricultural production after the year 2000, but this acreage will be minimized if new methods of water conservation are applied. Additionally, salt-tolerant crops such as rice, grain, and sugar beets may be introduced to extend the useful life of saline wells, and other crops requiring less water generally may be introduced. In Texas, for example, sunflowers are used to produce vegetable oil instead of other oil-seed crops requiring more water. Some of the irrigation measures which might be introduced to conserve water include the following:[12]

1. Application of water at primarily critical stages of development to reduce the water requirement as much as 50 percent. The time at which water is applied is as important as the amount used.
2. Sprinkler systems to reduce water consumption.
3. Conveyance piping to avoid water loss from seepage and evaporation.
4. Drip and trickle systems to deliver water to the base of the plant. This method could save up to 50 percent of the water conventionally applied.
5. Subirrigation, in which perforated plastic pipes are laid beneath each crop row.
6. Narrow row spacing to reduce the acreage under irrigation.
7. Mulching and reduced tillage to allow better infiltration of rainfall.
8. Water harvesting often done by terracing to collect runoff from one area for reuse in another area.
9. Plant crop breeding to produce hybrid varieties with reduced water requirements.

Measures such as these may significantly retard the rate at which energy requirements to obtain groundwater increase, but even with these measures the withdrawals from ground storage will probably exceed recharge, the water table will drop, and increased energy will be required for pumping. Additional data are needed before the impact of these agricultural techniques can be quantified. Whether or not the total energy requirement in the area continues to increase depends upon the number of acres farmed under conditions of rising irrigation costs.

Irrigation in the High Plains of Texas

The second irrigation area considered is in the high plains of Texas. The Texas high plains are part of the west central high plains of the United States, extending from Nebraska southward through a small portion of eastern Kansas and western Colorado and into the Texas Panhandle (see Figure 42.)



A third of this province is in Nebraska, a fourth in Texas, and a sixth in Kansas; the remainder is in Colorado, New Mexico, Wyoming, South Dakota, and Oklahoma.

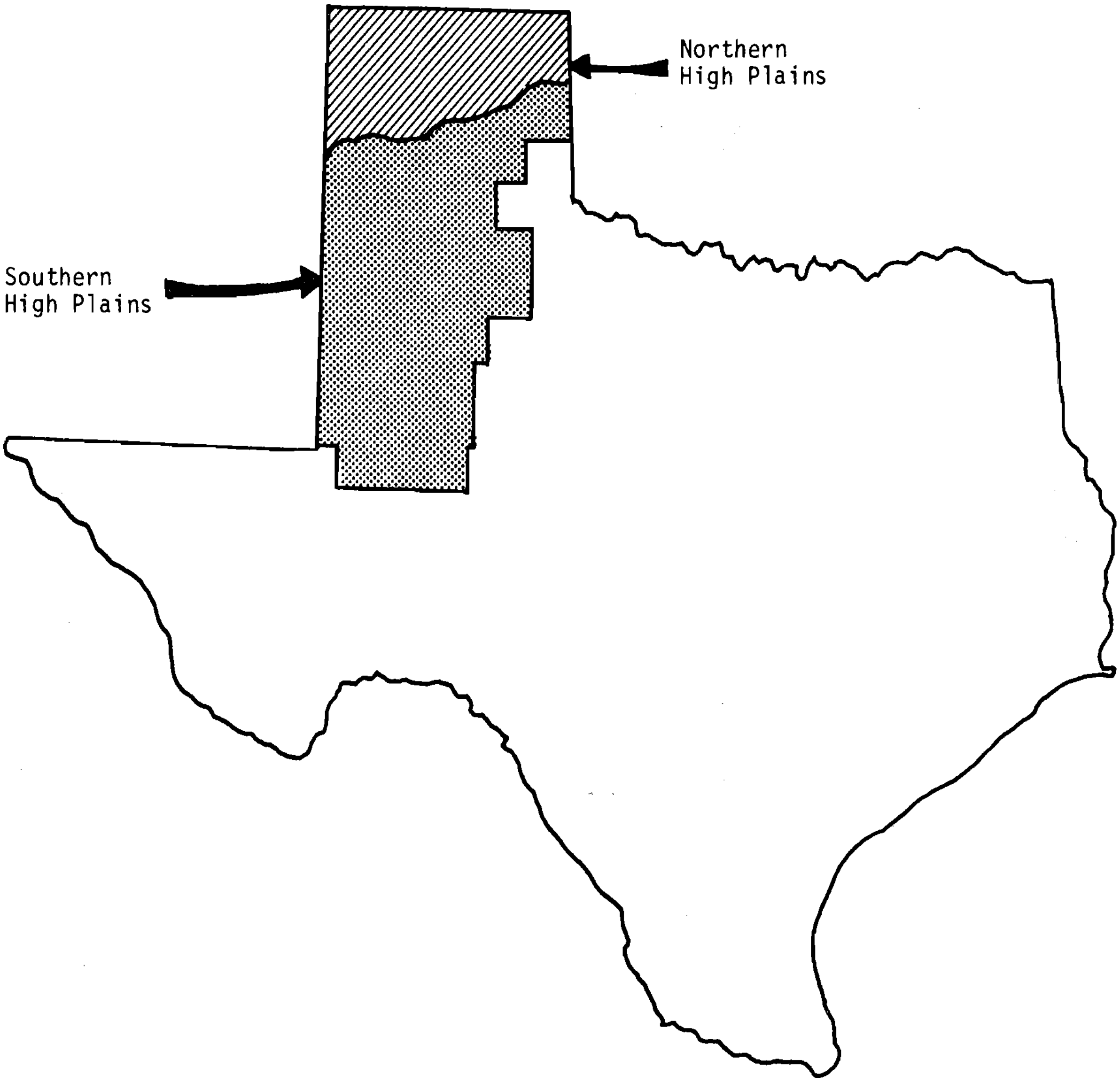
Source: Lohman, S. W. 1953. "High Plains of West-Central U.S., General Aspects." *The Physical and Economic Foundation of Natural Resources*, Part IV, Chapter 4. Subsurface Facilities of Water Management and Patterns of Supply-Type Area Studies. Interior and Insular Affairs Committee, House of Representatives, U.S. Congress, p. 71.

Figure 42. The high plains of the west-central United States.

Researchers have drawn the boundaries for the Texas high plains in slightly different ways, but in this study the northern high plains, with an area of approximately 9,300 mi, is considered to include the 12 counties listed below that lie north of the Canadian River: Dallam, Hartley, Sherman, Moore, Hansford, Hutchison, Ochiltree, Lipscomb, Roberts, Hemphill, Oldham, and Potter (see Figure 43). The southern high plains are a larger area of approximately 25,000 sq mi lying south of the Canadian River. The following 34 counties are included in the southern high plains: Deaf Smith, Randall, Carson, Armstrong, Gray, Parmer, Castro, Swisher, Briscoe, Bailey, Lamb, Hale, Floyd, Cochran, Hockley, Lubbock, Crosby, Yoakum, Terry, Lynn, Dickens, Garza, Gaines, Dawson, Borden, Andrews, Martin, Howard, Ector, Midland, Wheeler, Donley, Motley, and Glasscock.

Major irrigation areas in the state included in the high plains are located in Figure 44. Irrigation first began in the southern high plains around 1914 and increased slowly until 1945, after which time irrigation in the area expanded rapidly.[13] Irrigation in the northern high plains was introduced much later during the drought years of 1951 to 1957.[7] Since the mid-1960s, irrigation has been declining in the southern plains, but irrigated acreage in the northern plains has continued to increase through the mid-1970s. The present demand for water in this area is likely to be the peak demand.

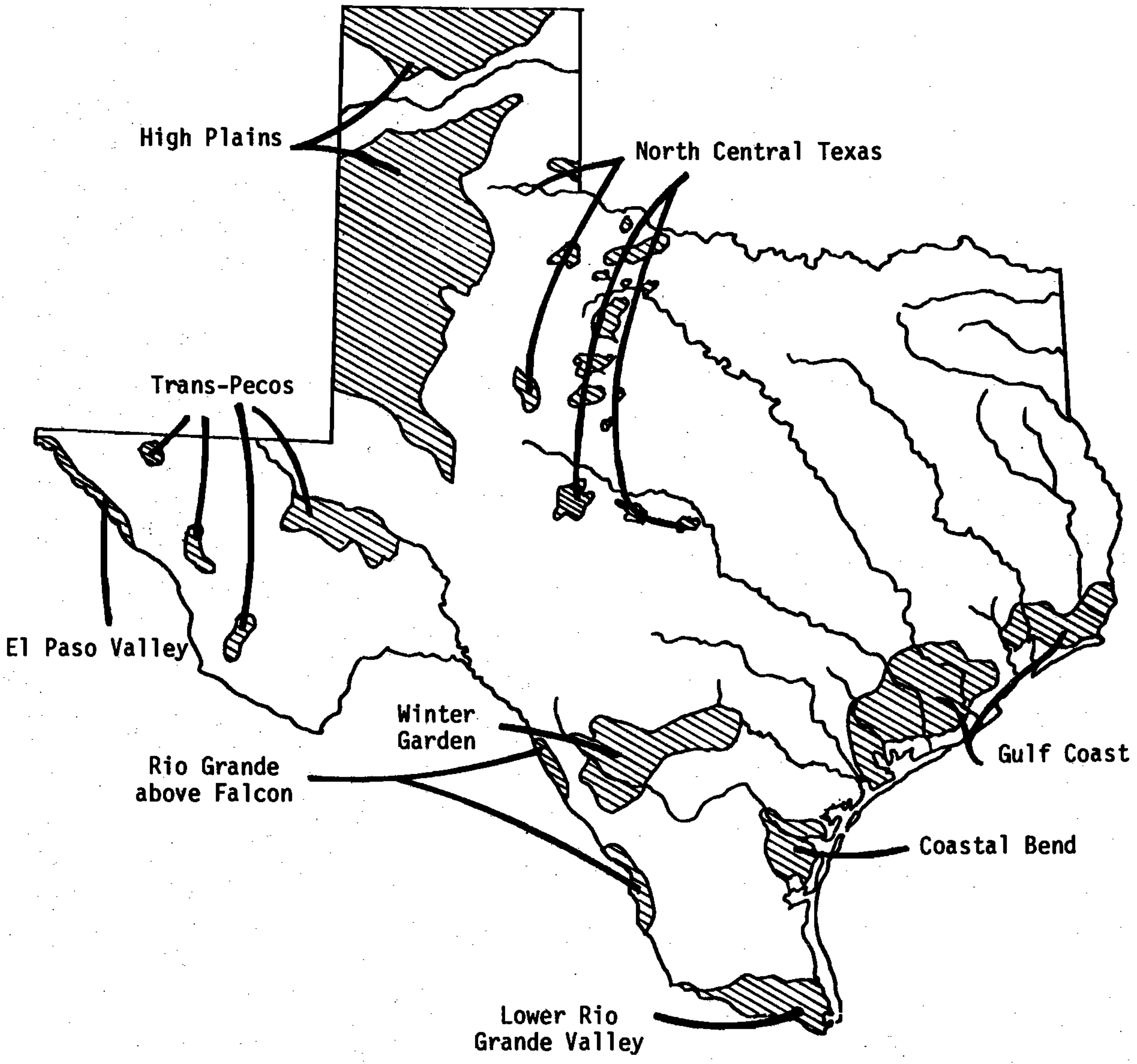
The high plains are underlain by the Ogallala Formation, which is a large unconfined aquifer. An unconfined aquifer occurs under water table conditions. Figure 45 shows the location of this aquifer, which was created well over a million years ago and is the major water source for irrigation in the area. Because the aquifer is geologically isolated from other water sources such as the Pecos River, the Canadian River, and Rocky Mountain streams, rainfall is the only source of recharge. Rainfall, which is usually less than 21 in./year, naturally recharges the aquifer by only about 0.0625 in. annually.[13] Consequently, for the entire history of irrigation in the high plains, withdrawals have exceeded natural recharge to the aquifer, resulting in mining of the aquifer. An estimate by W. L. Broadhurst (1958) indicates that approximately 130 x 10^6 mil gal of water were in the Ogallala Aquifer before irrigation began.[13] A 1974 estimate indicates that in the northern high plains approximately 52 x 10^6 mil gal can still be recovered from the aquifer for irrigation, while in the southern high plains only about 40 x 10^6 mil gal of groundwater



High Plains Region of Texas

Source: Texas Water Development Board. 1977. *Continuing Water Resources Planning and Development for Texas—DRAFT*. Vol 1 (of two). *Importance of Water to Texas*, Part III, p. III-40.

Figure 43. The northern and southern high plains.



Source: Texas Water Development Board. 1977. *Continuing Water Resources Planning and Development for Texas—DRAFT.* Vol. 1 (of two). *Importance of Water to Texas,* Part III, p. III-7.

Figure 44. Principal irrigation areas in Texas.

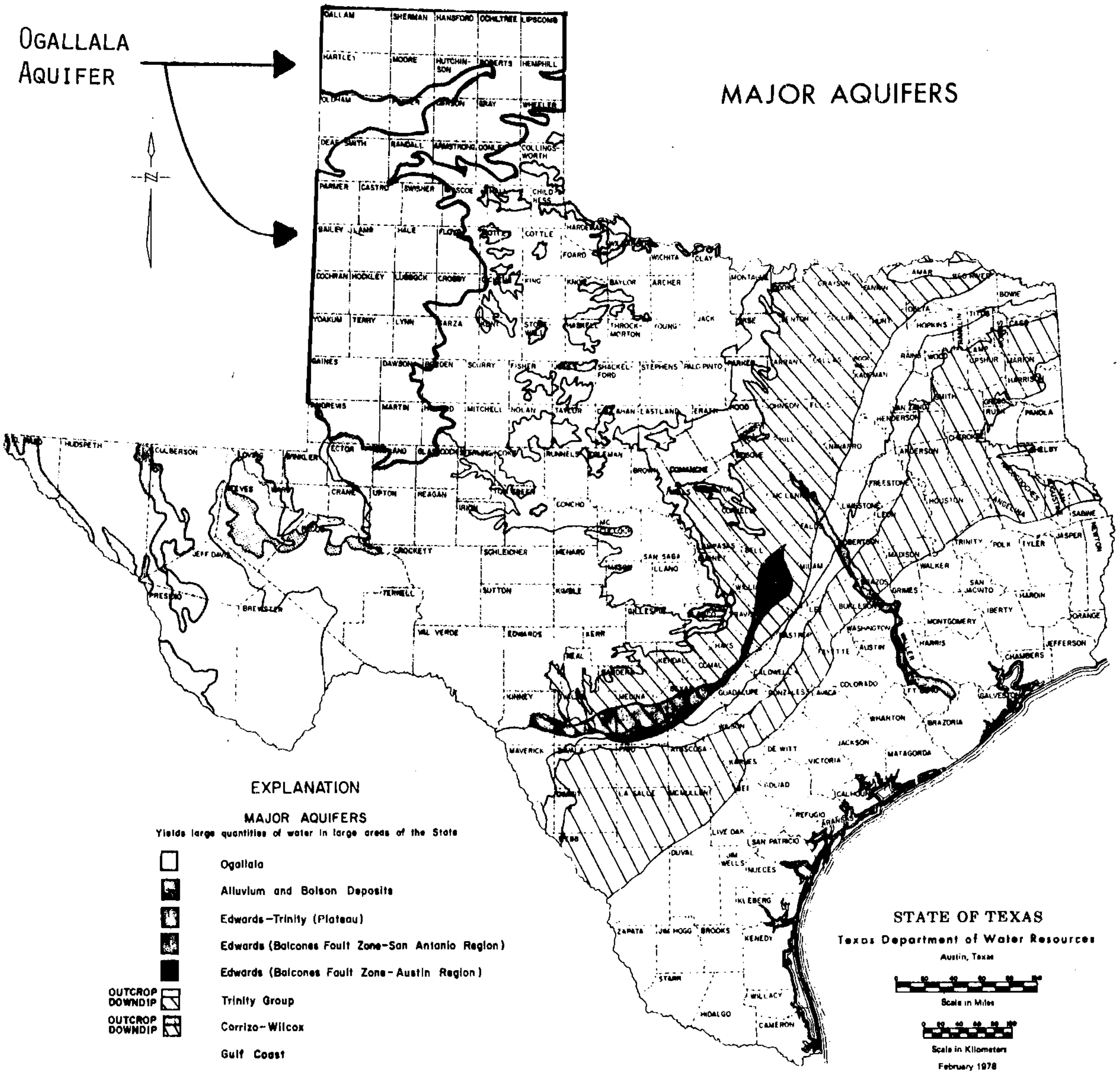


Figure 45. Location of the Ogallala Aquifer.

remain for use.[12] Together these reserves comprise 70 percent of the water initially available. Projections by the Texas Water Development Board, however, indicate that the total depletion of the groundwater sources available for irrigation in the high plains may occur by 2040.[12]

Major crops in the northern plains include corn, wheat, and maize, while in the southern plains cotton, grain sorghum, wheat, and corn predominate. For the high plains as a whole, the largest cash value crop of 1972 was cotton (\$389 x 10^6), followed by irrigated food grains (\$195 x 10^6) and feed grains (\$306 x 10^6).[12]

To calculate the energy required historically to obtain water for irrigation in the high plains and to project future energy demands for water, several data sources are combined. No attempt is made here to include the energy required to drill irrigation wells or to operate water distribution systems in the fields. Water withdrawals for 1949 and 1955 are estimated by taking irrigated acreage from a study by V. T. Clover[13] and multiplying by an average (1948 to 1960) water requirement per acre of 0.381 mil gal. For the years 1958, 1964, 1969, and 1974 the irrigated acreage and water withdrawals are taken from Report 196 by the Texas Water Development Board.[14] For the years after 1974, projected future demand for irrigation water is taken from the *1977 Water Resources Planning--Draft* of the Texas Water Development Board.[12] The projections contained in the draft copy are based on historic trends in water use, on availability of land for irrigation, and on the geological and hydrologic characteristics of the Ogallala Aquifer. It is also assumed that water beneath a section of land will be used to irrigate the specific section. These projected numbers are tentative and have not yet been cleared for final publication, but give a reasonable estimate of conditions that will prevail barring major economic or agricultural changes in the area. These projections indicate that by 2030 approximately 20 x 10^6 mil gal of recoverable groundwater will remain in the northern high plains and that the acreage under irrigation will decline from 1.3 x 10^6 acres in 1974 to 1.0 x 10^6 acres in 2030. In the southern high plains, projections indicate that only 5 x 10^6 mil gal will remain for use in 2030 and that acreage under irrigation will decline from 4.5 x 10^6 acres in 1974 to 1.0 x 10^6 acres in 2030. This decrease represents an overall decline in irrigated acreage of 66 percent. Table 73 presents estimated acreage under irrigation and water withdrawals for each year considered in this high plains study.

Table 73

High Plains Water Withdrawals and Primary Energy Consumption for Irrigation

		10^6 mil gal	Average Depth to Water (feet)	MJ/mil gal/ foot lift	Total Energy MJ x 10^6	MJ/ mil gal	10^6 Acres Irrigated
1949	HP*	0.6	(64)	117	4,493	7,488	1.7
	NHP*						
	SHP*		64				
1955	HP	1.5	(82)	117	14,391	9,594	4.3
	NHP						
	SHP		82				
1958	HP	1.691		117	19,514	11,540	4.5
	NHP	0.129	191		2,883	22,349	0.3
	SHP	1.562	91		16,631	10,647	4.2
1964	HP	2.533		117	35,766	14,120	5.2
	NHP	0.296	209		7,238	24,453	0.7
	SHP	2.237	109		28,528	12,753	4.5
1969	HP	2.124		117	36,267	17,075	5.6
	NHP	0.466	224		12,213	26,208	1.2
	SHP	1.658	124		24,054	14,508	4.4
1974	HP	2.686		98	42,624	15,869	5.8
	NHP	0.616	239		14,428	23,422	1.3
	SHP	2.070	139		28,197	13,622	4.5
1980	HP	1.53		98	28,780	18,810	
	NHP	0.55	256		13,798	25,087	
	SHP	0.98	156		14,982	15,288	
1990	HP	1.33		83	23,744	17,853	
	NHP	0.52	276		11,912	22,908	
	SHP	0.81	176		11,832	14,607	
2000	HP	1.14		60	16,346	14,339	3.2
	NHP	0.49	296		8,702	17,759	1.2
	SHP	0.65	196		7,644	11,760	2.0
2010	HP	0.95		60	15,072	15,865	
	NHP	0.46	316		8,722	18,961	
	SHP	0.49	216		6,350	12,959	
2020	HP	0.84		60	14,414	17,159	
	NHP	0.42	336		8,467	20,159	
	SHP	0.42	236		5,947	14,159	
2030	HP	0.72		60	13,344	18,637	2.0
	NHP	0.39	356		8,352	21,361	1.0
	SHP	0.32	256		4,992	15,360	1.0

*HP = High Plains
*NHP = Northern High Plains
*SHP = Southern High Plains

An assessment of the energy required to obtain these withdrawals requires two additional pieces of information. First, depth to water table must be determined and second pumping efficiencies must be considered. The present average water-table levels of 250 ft in the northern high plains and 150 ft in the southern high plains were reluctantly suggested by irrigation specialists in the high plains.[15] Their reluctance to give an average depth stems from the fact that within a mile radius one well may be pumping from a depth of 500 ft while the water table for a second, nearby well may be 75 ft. As one high plainsman put it, "It's like asking a man with one foot in the ice and the other foot in boiling water what his average temperature is." It should, therefore, be emphasized that results obtained using average depth and average rate of decline are indicative of trends and not precise quantitative results. Over fairly extended periods of time, the average rates of decline have occurred similarly in both the northern and southern high plains. For years prior to 1974, an average annual decline of 3 ft is used to calculate the depth of the water table in early years. In 1975 and 1976, there was increased pumpage in both the northern and southern plains, and the average decline in the water table increased to about 4 ft. In the future, increased energy costs combined with increased depths to water will cause a reduction in the irrigated acreage unless an unexpected escalation in the cash value of crops occurs. Consequently, the decline in the water table for the years after 1976 is estimated at 2 ft annually. The decline in the water table and the change in irrigated acreage over time is presented graphically in Figure 46.

Pumping efficiencies in the high plains have been influenced by the abundance of natural gas in Texas. Historically low prices for natural gas are reflected in the fact that at present 65 percent of the wells use natural gas for pumping while 33 percent use electricity and 2 percent use other fuels such as LP and diesel fuel.[16] In addition, low natural gas prices have offered little incentive for high plains farmers to invest in better pumps and improved efficiency. In the future, however, higher energy prices will significantly cut the economic lifetime of older pumps and promote an increase in electrical pumping and in the pumping efficiencies for all types of pumps. This tendency toward improved efficiency is included in the energy calculations for irrigation in the high plains.

For the years before 1974, pumping efficiencies are based on a study by the Agricultural Engineering Department of the Texas Technical College.[17] A survey of 46 wells with natural gas fuel sources was conducted between 1964 and 1967 and indicates a median fuel requirement of 107 cu ft of natural gas or 117 MJ to lift one mil gal one ft in height (117 MJ/mil gal/ft lift). This

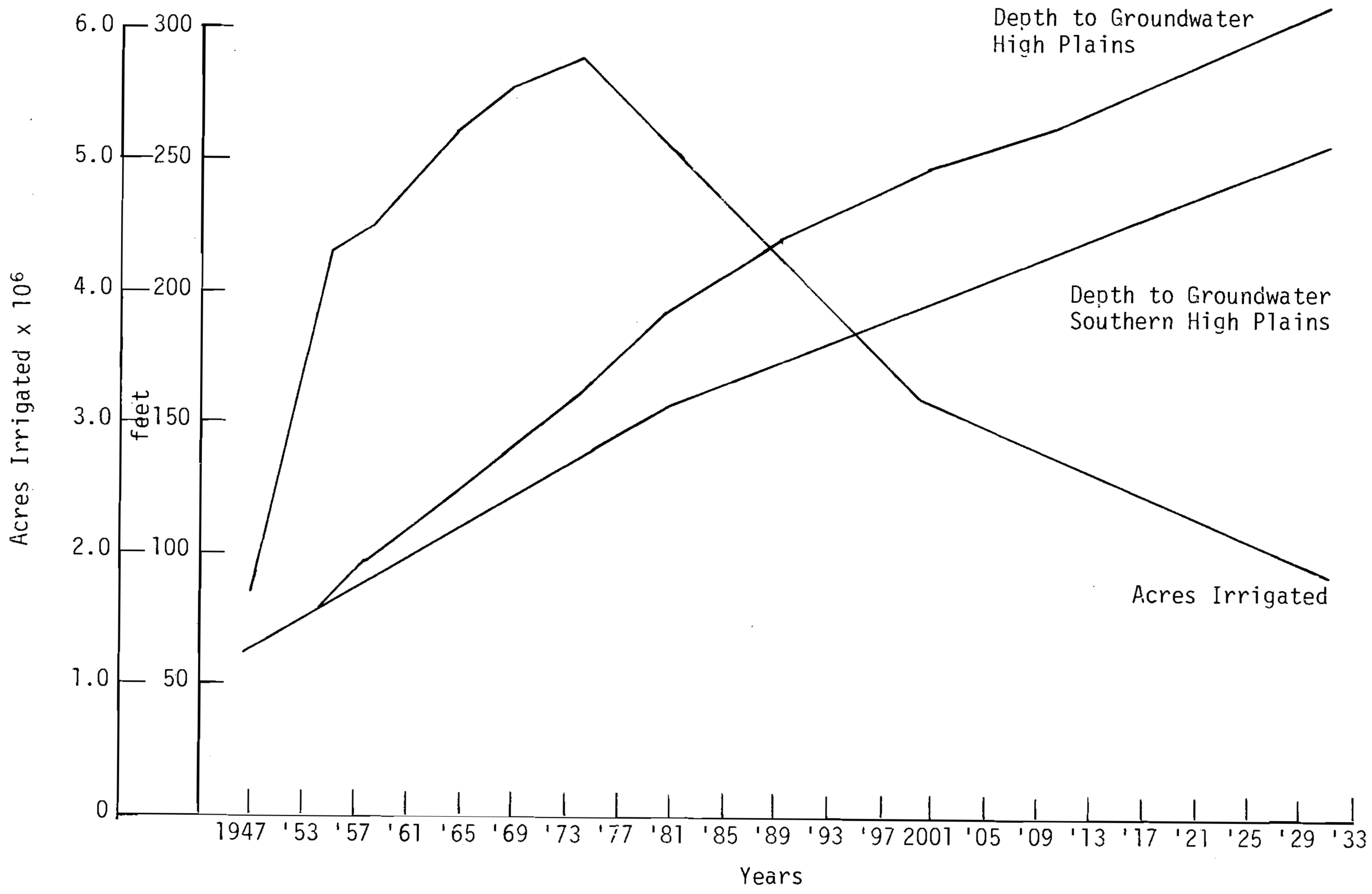


Figure 46. Acres irrigated and depth to water table in the high plains of Texas.

energy requirement is used in Table 73 to calculate the energy requirement for pumping through 1969. In 1974 the present distribution of pump types, i.e., 67 percent natural gas (and other) and 33 percent electrical, is used to determine a weighted average equal to the energy requirement per foot lift in 1974. Assuming that natural gas pumps require 117 MJ/mil gal/ft lift and that electrical pumps at 60 percent efficiency require 60 MJ/mil gal/ft lift (primary energy), the 1974 weighted average is 98 MJ/mil gal/ft lift. This value is used for the 1974 and 1980 calculation in Table 73. For 1990 another weighted average is taken. In this year, it is assumed that 60 percent natural gas (and other) pumps are used and have an improved efficiency of 15 percent. These pumps now require 99 MJ/mil gal/ft lift. The electrical pumps, which represent 40 percent of the total, are estimated at the same 60 percent efficiency, and the weighted average for 1990 is 83 MJ/mil gal/ft lift. For the year 2000 and those following, even better efficiencies are expected. Because Texas has long-term natural gas contracts with other parts of the country, and because these contracts take priority over Texas consumers, it is possible that electrical pumping will dramatically increase in future years. Consequently, for 2000 and later years, an energy requirement of 60 MJ/mil gal/ft lift is assumed. It should be noted that, even taking into account the primary energy of electricity, it is still more efficient to replace present low-efficiency fossil fuel pumps with electric units.

Multiplying mil gal of water withdrawn x depth to water x MJ/mil gal/ft lift gives a calculation of the total energy required for irrigation in any given year. Table 73 presents both the total primary energy requirement and the primary energy requirement per mil gal (depth to water x MJ/mil gal/ft lift). Of the years for which specific data are presented, the total primary energy requirement for the high plains is greatest in 1974. For the northern high plains the total energy requirement in 1974 is also greatest, while for the southern high plains the greatest total energy requirement occurred in 1964, reflecting the fact that irrigation was first introduced in the southern high plains and began declining earlier than in the north. It might be that, if data were available for the high plains in 1975 and 1976, these years would have an even higher total energy demand, but the import of the time profile is clear. A combination of reduced acreage under irrigation and improved pumping efficiencies will inevitably cause a decline in the total energy required unless crop prices increase radically and increased costs of irrigation can be met by a larger percentage of farmers in the area. The data in Table 74 indicate that between 1974 and 2030 the total primary energy requirement should decline about 69 percent for the high plains as a whole. In the southern high plains the requirement in 2030 will be 82 percent lower than in 1974. For the northern high plains a 42 percent decline in total energy will occur between 1974 and 2030.

Table 74

High Plains Irrigation Changes in Water and Primary Energy Consumption

	1974	2030	Change over 1975
Water Use (mil gal x 10^6)			
High Plains	2.69	0.72	-73%
Northern High Plains	0.62	0.39	-37%
Southern High Plains	2.07	0.33	-84%
Depth to Water (ft)			
High Plains	162	311	92%
Northern High Plains	239	356	49%
Southern High Plains	139	256	84%
Energy Use (Total MJ x 10^6)			
High Plains	42625	13344	-69%
Northern High Plains	14428	8352	42%
Southern High Plains	28197	4992	-82%
MJ/mil gal			
High Plains	15869	18637	17%
Northern High Plains	23422	21361	- 9%
Southern High Plains	13622	15360	13%

The same trends do not exist for the energy required per mil gal (also presented in Table 74). In the southern high plains the energy required per mil gal of water has increased 13 percent between 1974 and 2030, while it has actually decreased 9 percent in the northern plains. This result occurs because the water table in the north is approximately 100 ft lower than in the south. Consequently, improvements in pumping efficiency have a greater effect in the north than in the south. For the high plains as a whole, the energy required to obtain each mil gal of water for irrigation increases 17 percent, which exceeds the change in the southern high plains and the northern high plains because a weighted average of the water-table depth for the high plains as a whole gives an increase of 149 ft between 1974 and 2030. This increase is significantly greater than the change of 117 ft in the water table for the northern and southern high plains. The total energy requirement in the high plains is presented graphically for the years between 1949 and 2030 in Figure 47. Figure 48 represents energy required per mil gal pumped for this same time period.

Despite gains made from increasing pumping efficiency, more energy will be required in the high plains per unit of water used for irrigation in the future. Lowering of the water table and rising energy prices of recent years have resulted in steeply rising costs of irrigation. As a result much research in the high plains is being devoted to development of improved agricultural techniques which increase the efficiency with which water is used for irrigation. Another prominent area of research is development of hybrid crop varieties which require less water or have prolonged development so that natural precipitation can be more efficiently utilized. For irrigated acreage that is only marginally profitable, a movement from irrigation to dryland agriculture is under way. In dryland farming only a portion of the acreage is used to grow feed crops for cattle that roam the remaining untended acreage. This trend first gained momentum in the 1960s, when depressed cotton and wheat prices caused farmers to diversify.[18] Cattle were an attractive possibility because grain sorghum grown in the area is ideal cattle feed and beef prices were more stable. Dryland farming may form the economic base for the high plains of the future if water supplies to the area are not somehow increased.

Widespread removal of acreage from irrigation, however, has serious implications for the present-day agribusiness economy of Texas as well as for produce availability throughout the nation and possibly the world. As a result, several water importation proposals have been developed in an effort to maintain and even increase present levels of irrigation in the high plains. Any importation scheme would be a major project requiring federal funds for completion. The official proposal by the state of Texas has been prepared by the Texas Water Development Board and is presently undergoing revision, although federal participation has not yet been assured. Discussed below is

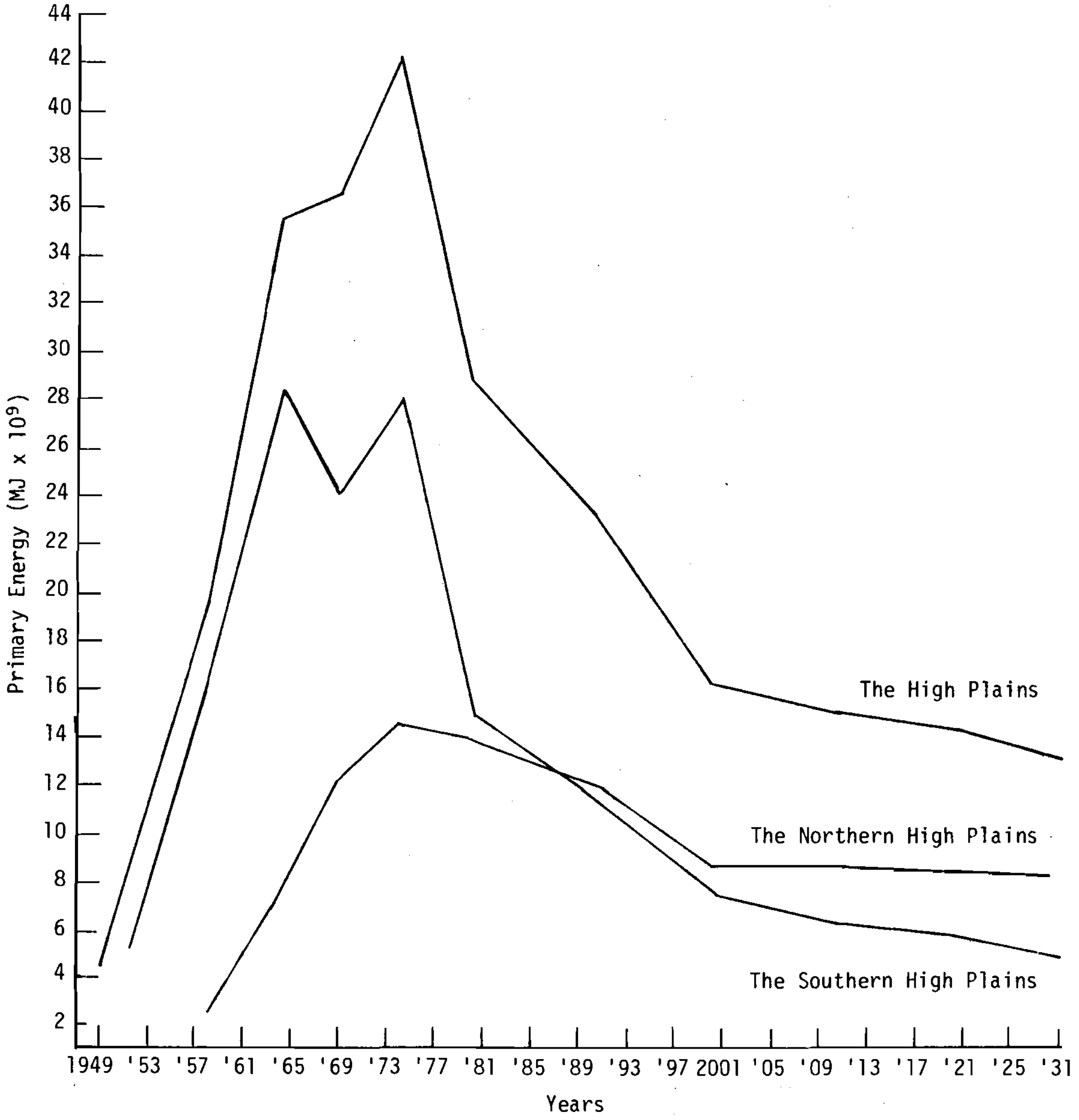


Figure 47. Total primary energy to supply water for irrigation in the Texas high plains.

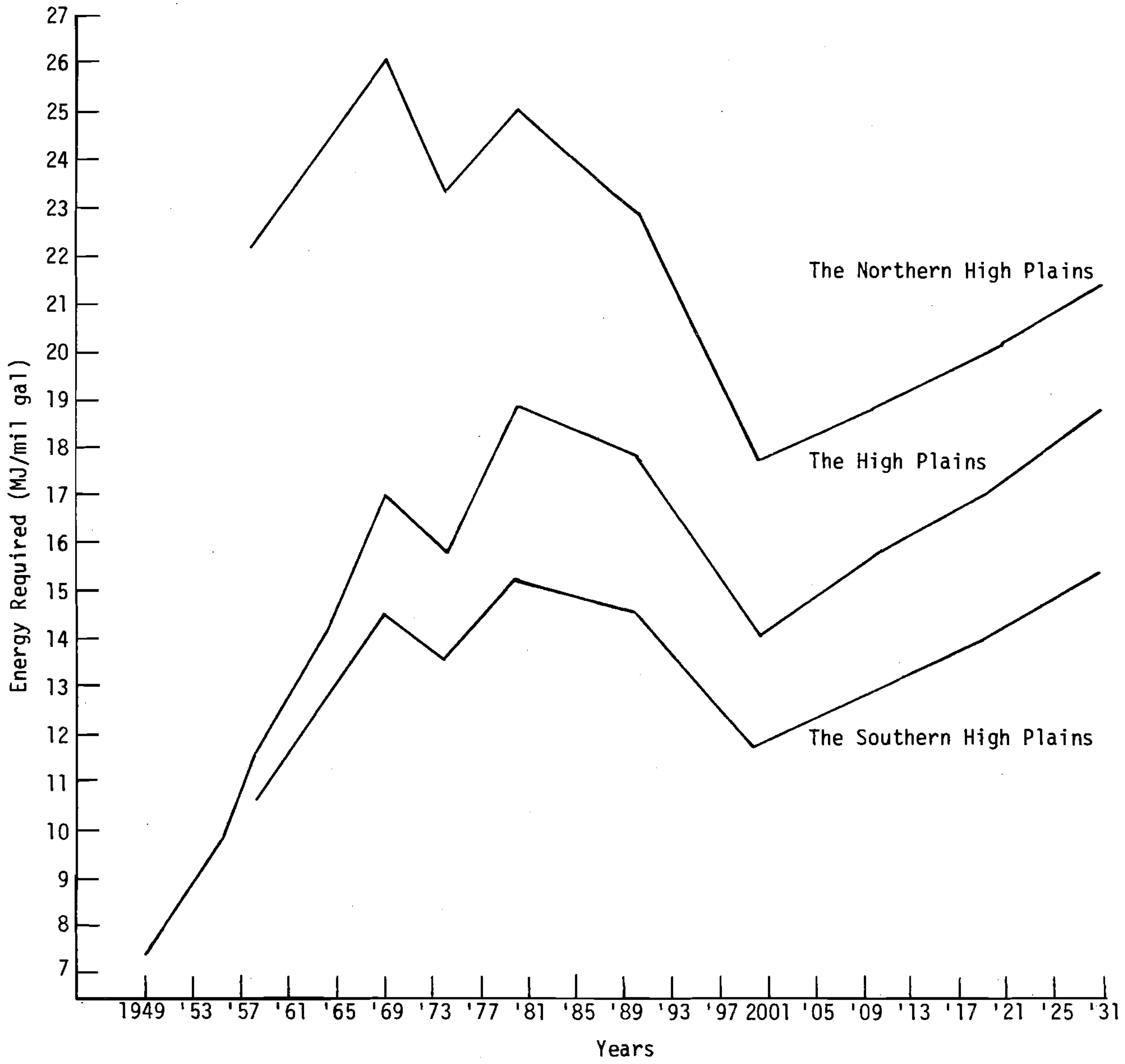
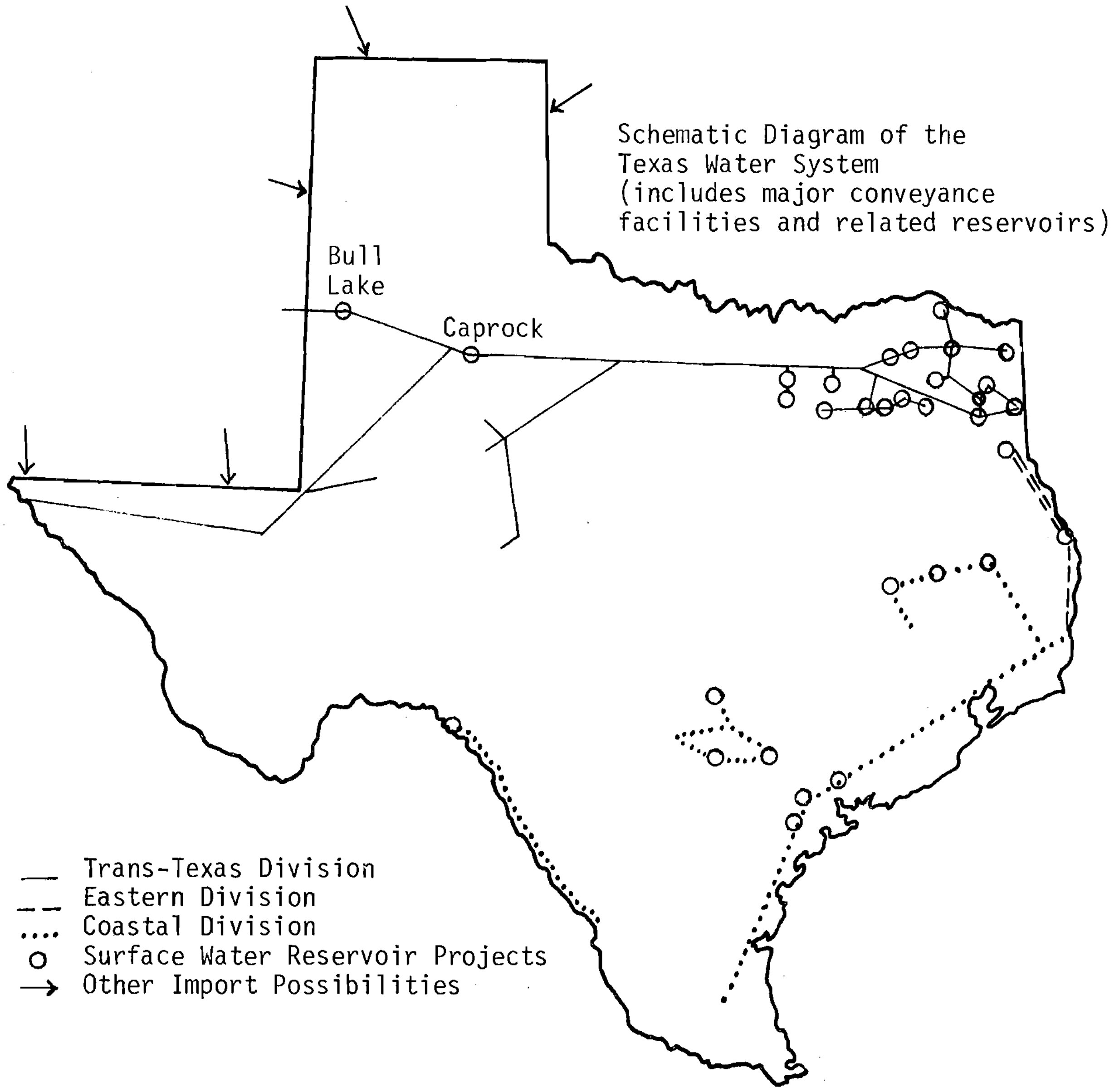


Figure 48. Primary energy required per million gallons of water obtained for irrigation in the Texas high plains.

the water plan presented in the 1968 summary.[19] This plan is by no means a reality. It may be rejected altogether, revised, or replaced with other alternatives. It is discussed here only as an example of the kinds of changes that could occur in the future energy requirements for irrigation in the high plains.

The three main parts of the 1968 water plan are the Trans-Texas Division, the Coastal Division, and the Eastern Division (see Figure 49). The Eastern Division is designed to deliver out-of-state imports to the Trans-Texas and Coastal Divisions. The Coastal Division will send water to the Winter Garden area of Texas as well as to the Guadalupe and San Antonio River Basins. The Trans-Texas Canal is designed to transport both imported water and excess supply from the major rivers of Eastern Texas (Lower Red, Sulphur, Cypress Creek, Neches, and Sabine Rivers) to western Texas and New Mexico. The Trans-Texas Canal would serve north-central Texas, the high plains, the Trans-Pecos area, and New Mexico. Approximately 3.3×10^6 mil gal/year will be transported through the canal, and of this total 2.5×10^6 mil gal are intended for irrigation. The canal, fed by reservoirs in northeast Texas, would begin at the upper Sulphur River Basin divide and travel the entire width of Texas. Water destined for the high plains would be stored in the Caprock Reservoir and Bull Lake Complex, identified in Figure 49. Water travelling to these storage points will be lifted a total of 2700 ft, and the system operating at full capacity is estimated to require approximately 1333×10^6 MJ daily. This energy requirement, divided by the daily design capacity of the system (8958 mil gal), gives an approximate energy requirement of 148,805 MJ/mil gal transported across Texas to the Caprock and Bull Lake Reservoirs.

No final decision has yet been made regarding the best area from which to draw out-of-state supplies. One possibility might be to take water from the Arkansas River through Oklahoma. Another suggestion is to carry water from the Mississippi River via the Red River to the Texas Panhandle, and a third possibility would be to take water from the Mississippi River across Louisiana to eastern Texas. The latter possibility is particularly attractive because water is generally more available at lower points of elevation and minimizes foot-head loss. A very rough estimate of the energy required to move water from Louisiana to Texas is calculated using the following assumptions. First,



Source: *The Texas Water Plan—Summary*. The Texas Water Plan, Description of Physical Works, 1968. Texas Water Development Board, p. 13.

Figure 49. Proposed transfer of water within Texas.

it is assumed that the imported water is transported about 150 mi across the northern border of Louisiana to Texas at an average head loss of 0.3 ft per canal mile, and over a 200-ft increase in elevation. Second, it is assumed that electrical pumps are used with a 65 percent efficiency (53 MJ/mil gal/ft loss). Multiplying the distance transported times the head loss and then adding to this product the rise in elevation gives a total head loss of 245 ft. Head loss multiplied by the energy requirement per foot lift gives an approximate energy requirement of 12,985 MJ for each mil gal of water imported to Texas.

Adding the energy requirement of importation, transportation across Texas and distribution within the high plains gives a total energy requirement of 162,585 MJ for each mil gal moved from out of state to irrigation in the high plains.

Importation from Louisiana	12,985 MJ/mil gal
Transport across Texas	148,805 MJ/mil gal
Distribution in high plains	795 MJ/mil gal
Total primary energy requirement	162,585 MJ/mil gal

This energy required to import each unit of water to the high plains is about 10 times higher than the 1974 energy requirement for pumping groundwater in the high plains (15,869 MJ/mil gal). The projected energy requirement of 2030, 18,637 MJ/mil gal pumped, is lower by a factor of nine than the energy requirement for use of out-of-state water.

Because a project of this magnitude could take twenty-five years or more for completion and because no specific plan has to date been approved, water importation is not likely to occur before 2010 at the earliest. Texas planners, however, feel confident that some source of imported water will be available for use in the high plains before 2040, when total depletion of groundwater for irrigation is likely. The energy requirements presented in Table 73 will significantly underestimate the energy requirements for any year in which water importation becomes a reality.

While the energy requirements of water-supply schemes are important to consider in choosing among competing alternatives, they are by no means the only or even the most relevant criterion by which choices should be made. Economic objectives, social benefits, protection of food supplies, capital costs, and many other factors should be fit into a calculation of the total social costs and total social benefits to be derived from any of the plans designed to increase water availability in the area.

San Carlos Irrigation Project

The San Carlos Irrigation Project, which is operated and maintained by the Bureau of Indian Affairs of the U.S. Department of the Interior, is located near Coolidge, Arizona, in the Casa Grande Valley. Coolidge is in Pinal County and is located approximately 56 mi southeast of Phoenix and 68 mi northwest of Tucson. The Gila River, the major source of water in the area, flows directly through the project.

The project encompasses approximately 100,000 acres, half of which are part of the Gila River Indian Reservation. The other 50,000 acres are privately owned by non-Indians. The San Carlos Project is administered by three organizations: the Indian Works, the District Works, and the Joint Works. The Indian Works, which is under the jurisdiction of the Pima Agency of Sacaton, Arizona, is responsible for delivering the irrigation water allocated to the Gila River Indian Reservation. The District Works, a private organization, performs this same service for non-Indian lands. The Joint Works, which is under the jurisdiction of the U.S. Bureau of Indian Affairs, operates and maintains the portions of the project common to both the Indians and non-Indians, i.e., dams, storage reservoirs, canals, and irrigation wells.

The San Carlos Project is located in a region characterized by desert conditions. The lands of the project are flat and dry. Since the average annual rainfall is only 8.04 in., irrigation is a crucial factor in maintaining the productivity of the area. (The recent drought in the western states severely affected the project. At the time of this study, the amount of stored surface water was only 20 percent of the project's total capacity.)

The major crops grown on the project are cotton, alfalfa, maize, hegira, wheat, and barley, with cotton being the main cash crop (see annual crop report for 1976 shown in Table 75). Agriculture is the basis of the local

Table 75

1976 Crop Report for San Carlos Irrigation Project

	Unit	Acres	Yield	Average Acre Yield	Market Value Unit	Market Value Acre	Total Market Value
Barley	ton	4,696.70	8,449.22	1.80	$100.20	$ 180.36	$ 847,100
Beans	pound	20.00	40,000.00	2,000.00	0.20	400.00	8,000
Cotton, Short Lint	bale	15,242.76	40,178.89	2.64	357.04	942.61	14,339,673
Cotton Seed, Short Lint	ton		14,214.15	1.10	105.00	108.57	1,492,521
Cotton, Long Lint	bale	1,057.00	2,140.96	1.84	549.34	1,010.80	1,174,573
Cotton Seed, Long Lint	ton		930.97	0.80	105.00	84.00	97,751
Ensilage	ton	433.50	7,125.00	16.44	12.00	197.28	85,521
Grapes	pound	30.00	54,000.00	1,800.00	0.15	270.00	8,100
Hay-Alfalfa	ton	6,793.55	31,820.51	4.68	75.00	351.24	2,386,136
Hay-Miscellaneous	ton	102.00	411.50	4.03	65.00	261.95	26,719
Hegari	ton	80.00	80.00	1.00	90.00	90.00	7,200
Maize	pound	455.00	1,334,000.00	2,931.87	0.045	131.93	60,028
Okra	pound	5.00	5,000.00	1,000.00	0.15	150.00	750
Pasture-Alfalfa	acre	154.00					200
Pasture-Grain	acre	194.29					3,030
Pasture-Summer	acre	458.51					2,970
Pasture-Irrigated	acre	450.00	450.00	1.00	9.76	9.76	4,392
Pasture-Stubble	acre	3,711.00	3,711.00	1.00	9.21	9.21	34,178
Sugar Beets	ton	2,639.00	65,940.00	24.98	22.73	567.69	1,498,132
Wheat	ton	15,336.00	31,403.26	2.04	108.85	222.07	3,405,661
Lettuce	crate	160.00	80,000.00	500.00	3.00	1,500.00	240,000
Cantaloupes	crate	200.00	24,000.00	120.00	8.00	960.00	192,000
Melons	ton	791.00	9,492.00	12.00	80.00	960.00	759,360
Carrots	ton	150.00	2,250.00	15.00	120.00	1,800.00	270,000
Garden	acre	25.00	25.00	1.00	200.00	200.00	5,000
Sorghum Grain	ton	380.00	760.00	2.00	93.00	186.00	70,680
Corn	ton	45.00	90.00	2.00	93.00	186.00	8,370
Totals		53,609.31					$27,028,045
Less Double Cropped		865.00					
Net Acres Cropped		52,744.31					
Total Acres Irrigated		53,401.43					
Idle Not Irrigated		40,513.57					

Average Crop Value per Acre Cropped = $512.43

Source: *San Carlos Irrigation Project - Arizona - Annual Irrigation Report,* 1976, p. 25.

economy. Most people living in the area are economically tied to agriculture, either directly as farmers or indirectly as farm equipment suppliers.

The San Carlos Irrigation Project was created in 1930 upon the completion of the Coolidge Dam and Reservoir. The Coolidge Dam was constructed to provide a means of storing water from the Gila River, and a series of canals now carries the diverted water to nearby agricultural lands. This surface supply is supplemented with a number of irrigation wells located throughout the project. Though surface water is the primary source of water, groundwater is an important source of supply in dry years. In 1976, groundwater constituted 34 percent of the total amount of water supplied.

The energy required to supply water for the project is provided by purchased electrical power. The project does maintain its own power plant at Coolidge Dam, but for a number of years there has not been enough stored water to operate it. Furthermore, even when this generating plant is operating, the energy it produces provides only a small portion of the project's total energy requirements.

The primary energy requirement for pumping has been calculated using a conversion factor of 11.11 MJ/kwh. The direct energy requirement for supplying water can be calculated using a conversion factor of 3.6 MJ/kwh, which represents only the usable energy of each kwh and excludes energy inputs for electrical generation and transmission.

All of the energy required to supply the water needed for irrigation is consumed in the pumping of groundwater. Surface water is distributed by gravity flow, so this portion of the project does not require any expenditure of energy. Thus, the total annual amount of energy consumed is directly dependent on the amount of groundwater withdrawn. The project relies on its surface sources as much as possible, but the amount of surface water that can be supplied in a given year is governed by the amount of precipitation the area receives during that time.

The groundwater is obtained from a series of small aquifers rather than from one large aquifer. Consequently, the quality and depth of the groundwater vary throughout the project. Some project wells pump water from shallow aquifers, while wells in other locations must be drilled deep to reach water. Project administrators are unable to quantify the amount of groundwater remaining in the area because the groundwater is pumped from a series of aquifers instead of from a single continuous one.

As previously stated, the San Carlos Project includes approximately 100,000 acres of land. However, because of a limited supply of readily available water, not all of the 100,000 acres are developed. The actual number of acres cultivated fluctuates from year to year around an average of 50,000 to 55,000 acres. Almost all of the cropland is irrigated.

The acquisition and distribution of the project's surface water does not require any expenditure of energy and is, therefore, the most economic means of supplying water. For this reason, the number of acres farmed each year is dependent on the amount of rainfall the area receives. Groundwater, because it is a more costly source of water to develop, has not been tapped in all areas of the project. This situation is particularly true for Indian-owned land, The Indian farmers simply lack the capital necessary to drill more wells.

Long-term plans indicate that the number of acres cultivated will not increase. Present available sources of water will be utilized to maintain the cropland already in existence.

Even though no expansion in the acreage to be cultivated is expected, all indications are that the amount of energy consumed in supplying water for irrigation will increase. This fact is attributable to an increase in the amount of energy required to pump groundwater. Data specifying the approximate average static water levels for all of the project's wells reveal that groundwater levels are declining. These data are presented in Table 76 and illustrated in Figure 50. Groundwater is being withdrawn faster than it is being recharged. As the water levels decline, more energy will be needed to pump the groundwater to the surface. Thus, merely to maintain the present usage of groundwater will require additional energy.

Table 76

Historic Average Static Water Levels for All of the San Carlos Irrigation Project's Wells

Year	Average Depth to Groundwater (feet)
1936	43
1937	46
1938	46
1939	51
1940	54
1941	55
1942	50
1943	50
1944	52
1945	54
1946	58
1947	78
1948	73
1949	76
1950	80
1951	88
1952	89
1953	90
1954	100
1955	102
1956	107
1957	117
1958	118
1959	119
1960	121
1961	120
1962	128
1963	132
1964	142
1965	143
1966	138
1967	148
1976*	160
1977	170

*Data for years 1968-1975 were not available.

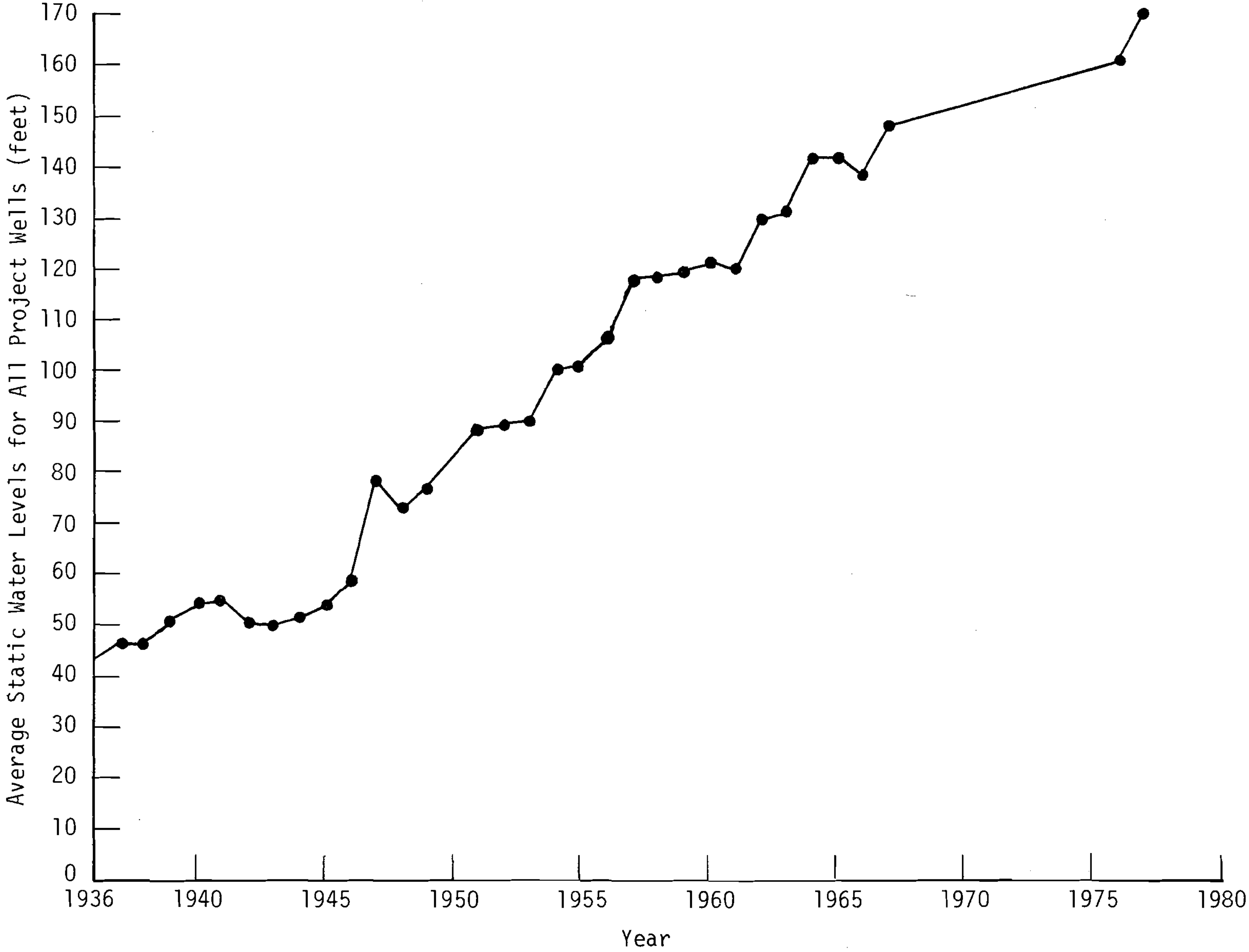


Figure 50. Average static water levels for all project wells during the years 1936-1977 for the San Carlos Irrigation Project.

To project the actual amount of energy that will be required to supply irrigation water for the San Carlos Project in future years, the historic amount of energy consumed per unit of water supplied was extrapolated using a linear regression. Data for the years 1935 through 1976 were averaged in five-year intervals, and these averages were extrapolated. Data back to the year 1935 were used to best capture the fluctuations in surface and groundwater usage. (A spokesman for the project indicated that a wet year usually occurs every fifth or sixth year, reducing the amount of groundwater used during those years.) The historic amount of energy required per unit of water supplied is presented in Table 77, and the projected energy requirement for the years 1980, 1990, and 2000 is presented in Table 78. Both the historic and projected energy requirements are illustrated in Figure 51. These projections are based on the assumption that groundwater levels will continue to decline at the same rate as in the past.

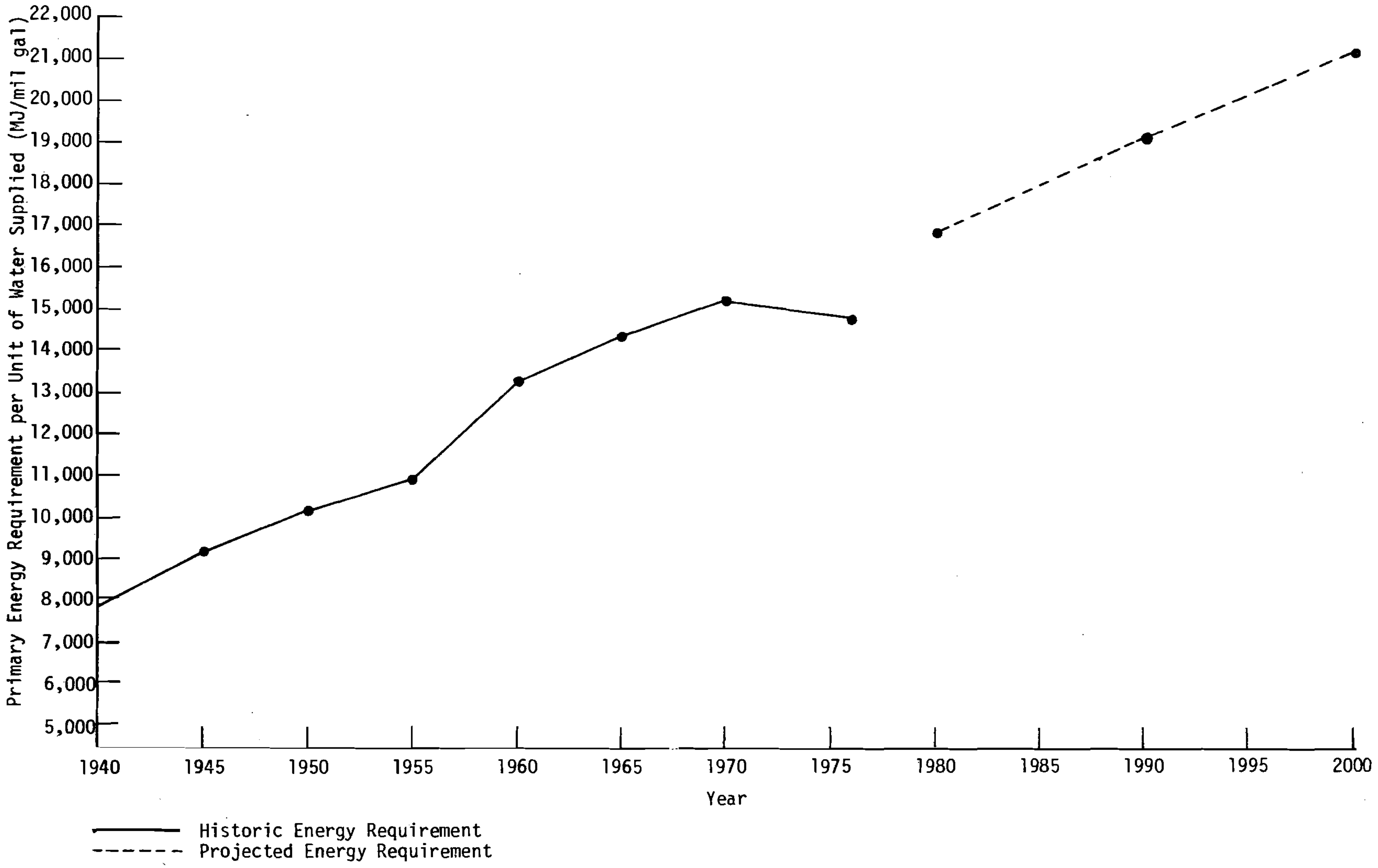
Table 77

Historic Primary Energy Requirement per Unit of Water Supplied for the San Carlos Irrigation Project

Years	Average Amount of Energy Required per Unit of Water Supplied (MJ/mil gal)
1935-1940	7,985.5
1941-1945	9,173.1
1946-1950	10,025.9
1951-1955	10,947.6
1956-1960	13,397.9
1961-1965	14,437.5
1966-1970	15,136.1
1971-1976	14,858.8

The amount of water to be supplied in future years is estimated to be 8.5438×10^{10} gal/year or 234.08 mgd. This figure is an average of the total amount of water supplied for the years 1934 through 1976. The projection is based on three assumptions:

1. The project will not develop any new sources of water supply, e.g., importation of water.



Note: The historic data is averaged in five-year intervals, so the average energy requirement per unit of water supplied for the years 1935-1940 is represented by the data point at 1940, 1945 represents the years 1941-1945, etc.

Figure 51. Historic and projected primary energy requirement per unit of water supplied for the San Carlos Irrigation Project.

Table 78

Projected Primary Energy Requirement per Unit of Water Supplied for the San Carlos Irrigation Project

Year	Projected Energy Requirement per Unit of Water Supplied (MJ/mil gal)
1980	16,871.0
1990	19,052.6
2000	21,234.2

2. There will not be a substantial increase in the number of acres irrigated.
3. Since the number of acres under cultivation will not increase significantly, the amount of water required for irrigation will remain relatively fixed.

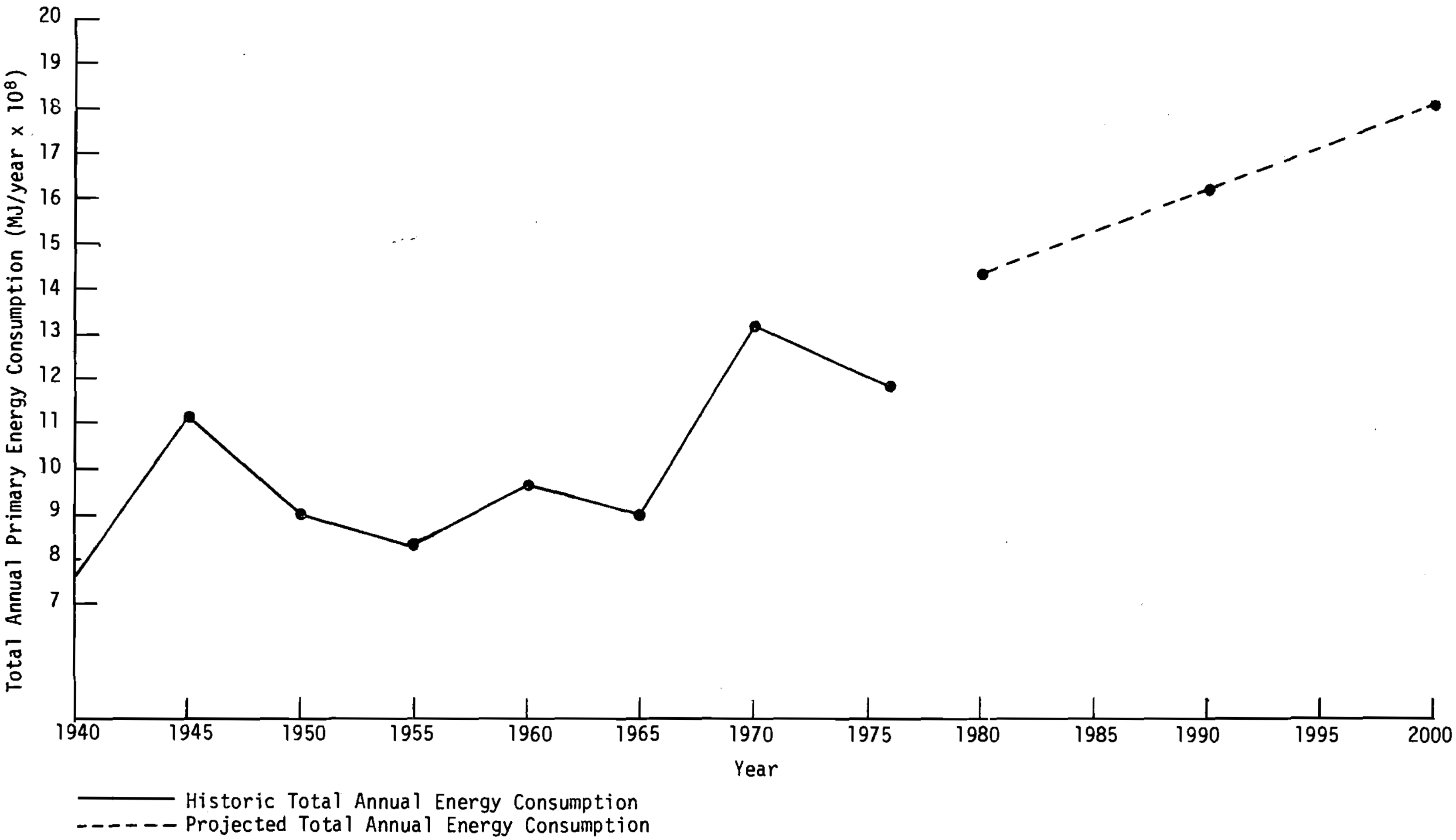
The projected total annual energy consumption was calculated by multiplying the projected energy requirement per unit of water supplied times the estimated future mgd times 365 days. These results are presented in Table 79 and illustrated in Figure 52.

Table 79

Projected Total Annual Primary Energy Consumption of the San Carlos Irrigation Project

Year	Projected Energy Requirement per Unit of Water Supplied (MJ/mil gal)	Projected Water Demand (mil gal/day)	Projected Total Annual Energy Consumption (MJ/year x 10^8)
1980	16,871.0	234.08	14.4
1990	19,052.6	234.08	16.3
2000	21,234.2	234.08	18.1

In 1975, the average amount of energy required per unit of water supplied was 14,524.6 MJ/mil gal, and the total annual amount of energy consumed was 12.6 x 10^8 MJ/year. These figures, when compared to the projection estimates for the year 2000 listed in Table 79, indicate that by the year 2000 there will



Note: The historic data is averaged in five-year intervals, so the average total annual energy consumption for the years 1935-1940 is represented by the data point at 1940, 1945 represents the years 1941-1945, etc.

Figure 52. Historic and projected total annual primary consumption for the San Carlos Irrigation Project.

be a 46.2 percent increase in the energy requirement per unit of water supplied and a 43.7 percent increase in the total annual amount of energy consumed. These values represent primary energy.

The projections presented in this study of the San Carlos Irrigation Project are only rough estimates of future energy consumption and are based on a particular set of assumptions. It should be pointed out that future energy consumption will be dependent on a number of factors, not all of which have been considered in this pilot study. The weather, for example, is the most deciding and perhaps the most unpredictable factor affecting water supply in this area. Future droughts, such as the extensive one the region experienced in 1977, would severely diminish the project's present sources of water. It is possible that groundwater supplies may be depleted by the year 2000, requiring the construction of expensive and energy-intensive water-acquisition projects if the present level of cultivation is to be maintained. Even if the groundwater is not totally depleted by the year 2000, it may decline to a level where pumping becomes prohibitively expensive. If water shortages occur in the future and new sources of water supply must be developed, the importance of the agricultural production in this area will determine whether or not the expense necessary to supply additional water is warranted.

Arizona is presently one of the most rapidly growing areas in the country, and water demand is a serious problem. Although this case study may not be a typical Arizona irrigation project with respect to the crops grown, local climatic conditions, or even the sources of water supply, it does represent the general conditions that prevail in Arizona. Agriculture is only one of many competing interests vying for a share of a limited supply of water. If agricultural growth is to be maintained, or, as the San Carlos Irrigation Project demonstrates, even if the present level of development is to be sustained, a significant amount of additional energy will be required. The results of this study indicate that the water and energy problems in Arizona merit further detailed study.

All three irrigation projects examined in this paper are located in the arid Southwest, and all are withdrawing groundwater at a rate faster than natural recharge. Virtually 100 percent of the high plains water supply comes from ground storage, while Kern County, California, uses 60 to 70 percent groundwater. In Arizona, the San Carlos Project uses only about 35 percent groundwater for irrigation. Because the energy requirements for ground and surface supplies usually vary independently of one another, their relative share of the total directly influences the evolution over time of energy required per mil gal of irrigation water supplied. The efficiency of pumping also differs in these areas and is an important factor in projecting unit energy requirements for irrigation. One salient and distinguishing characteristic of the high plains is the present transition to more efficient pumping units. Sudden changes in the price and availability of natural gas in this area are providing a major incentive for energy conservation. As a result, many old, inefficient pumps are presently being replaced, and the energy required to obtain each unit of groundwater is expected to actually decrease slightly between 1974 and 2000 even though the water table will decline over this period. There is clearly an upper bound to the pumping efficiency that can be achieved with present technology, but the increasing price of energy across the nation should, at least in the near term, stimulate capital investment to minimize energy costs. In the two other irrigation projects, where pumping efficiencies are not expected to increase as significantly the unit energy requirements of groundwater, pumping should increase in correspondence with the lowering of the water table.

In terms of the total energy requirements to supply water, the major difference among these projects is the change in irrigated acreage expected in the future. In the high plains of Texas, irrigated acreage is expected to shrink by approximately 45 percent between 1974 and the year 2000. In the San Carlos Project of Arizona, the amount of land irrigated will be virtually unchanged between 1975 and 2000. Kern County, in contrast to the other areas, is expected to increase the acreage under irrigation by about 16 percent between 1975 and 2000. Because the irrigated acreage in the San Carlos Project is essentially fixed, the increase in total energy is concommitant with the increased energy required per mil gal obtained. In Kern County, California, expanding agricultural production causes a greater increase in the total energy required between 1975 and 2000 than occurs in the energy required per mil gal. The change in total energy required over time in the high plains is particularly interesting because it accentuates the complexities of trend-line projection.

A decline in water table increases the energy required per unit of water pumped at a given pumping efficiency, but it may result in a reduction of the total energy requirement for the area. If increased pumping costs exceed the profits available from crop sales, land will be taken out of production. This current trend in the high plains could result by the year 2000 in a 45 percent reduction in irrigated acreage and a 60 percent reduction in total energy used to obtain water for irrigation. Looking past the year 2000, however, out-of-state water importation, if it occurs, will most likely cause a dramatic increase in the total energy required in this area.

Energy projections based on the physical characteristics of a water-supply system such as depth to groundwater and on historic trends in agricultural growth are improved if the economic conditions governing the future can be simultaneously projected. Increases in depth to groundwater, increases in energy costs, and increases in other costs of irrigating directly influence the demand for water as marginally profitable acreage is forced out of production. A decline in the supply of agricultural commodities may, however, have an equal and opposite reaction, increasing crop prices and drawing acreage back into production. An important refinement of this energy study, therefore, would be an examination of the influence that fluctuations in market prices for energy, crops, land, and other commodities related to irrigation have on the demand for water.

To assess the importance of changes in the projected energy requirements for these irrigation projects, data from the FEA Project Independence report are used.[5] FEA projections indicate that without energy conservation the increase in the overall demand for energy in the U.S. will increase approximately 69 percent between 1977 and 2000. Under conditions of an energy conservation scenario, the "Conservation Major Shift" case, a 46 percent increase in national energy consumption is projected from 1977 through 2000. Over this same time period, the total energy required for water supplies in the San Carlos Project and in Kern County, California, is projected to increase 44 percent and 63 percent, respectively. For the Texas high plains a 62 percent *decrease* is anticipated in the total energy required to supply irrigation water between 1977 and 2000. Based on the Project Independence data, increases in the energy required for these irrigation projects do not exceed projected increases in national consumption of energy under the base case scenario. Even under the FEA's long-term energy conservation scenario, only the Kern County area is projected to have energy requirements increasing somewhat ahead of the national average.

Because these irrigation projects are all located in water-short areas of the arid Southwest, they should represent upper bounds on the growth in energy required to supply water for irrigation. Water for irrigation in the Midwest and Southeast, for example, is more plentiful as a rule and often available from surface supplies. As a result, there will very likely be a slower growth rate in the energy required to supply water to these areas in the future than will occur in the irrigation projects presented. Large unexpected increases in the acreage under irrigation or the occurrence of pervasive drought, however, would greatly accelerate the rate at which energy is used to obtain water for irrigation. It is also probable that after the year 2000 interbasin water importation will be a more common means of obtaining water for irrigation. Water transfers over long distance or to high elevations significantly increase energy requirements for irrigation, as indicated by an evaluation of importation proposals in the Texas high plains. Importation of water from the Mississippi River to the Texas Panhandle, for example, could cause an order or magnitude increase in the energy required for each unit of water imported.

In short, an immense number of variables will interact to define the future demand for irrigation water and the associated energy requirement. Historic trends in weather patterns and economic conditions in agricultural markets, applied to specific areas, however, suggest that the energy required to obtain water for irrigation will not increase faster than the energy requirements for the nation as a whole, at least until the year 2000.

5 CONCLUSION

This report is a pilot study intended to determine if the growth rate in the energy required by water-supply and -treatment systems between 1977 and 2000 warrants an exacting, quantitative, and disaggregated analysis of these systems. Because the energy requirements for water supply and treatment require only about 2 percent of the national energy budtet, little attention has been given to the energy inputs required in operation of these systems. Detailed compilations of energy and material inputs to water systems have rarely been made. This pilot study, therefore, emphasizes only the primary energy required to operate each system as an aggregate.

The projected energy requirements of the six cities examined in this pilot study indicate that the energy needed to supply water will be a regional rather than a national problem. For example, in northern and eastern cities (such as Chicago), which have ample supplies of water, and in cities such as St. Louis and New Orleans, which have declining populations, the energy needed to supply water will not be a major concern. However, in the arid Southwest, a region with limited supplies of water and an increasing population, the energy needed to supply water will become increasingly important. After the year 2000, the energy to supply water will rise more rapidly as energy-intensive water-supply systems such as desalination, interbasin transfers, and water reuse projects become more widespread. In the Southwest particularly, water-conservation practices aimed at lowering the demand for water will be very important.

An analysis of the energy required for sewage treatment is presented for 12 geographical regions of the country as well as for the nation as a whole. Calculations based on USEPA data sources indicate that the growth rate in the energy required for sewage treatment across the United States and in each of the regions defined will be considerably higher than the growth in national energy consumption between 1977 and 1990. This high growth rate in the energy required for sewage treatment will occur because a greater percentage of the population will be serviced by municipal sewage facilities and increasingly stringent water-quality regulations will be enforced. After 1990, the growth rate in the energy required for sewage treatment may be even higher than in the preceding decade as increasing numbers of advanced-treatment facilities come on line.

Because the increase in energy requirements will be so rapid and because many technological treatment options are available to municipalities, a precise delineation of the energy requirements for different treatment strategies is desirable. Unlike the energy needs for water supply, which are regional in character and tied to specific geographical and topographical conditions, energy for sewage treatment is primarily influenced by technological factors. A careful description of the energy and material flows of alternative-treatment options should be prepared and used as an important determinant in decisions about which new plants will be built and how existing facilities will be upgraded. Increasing attention should also be given to the possibilities for energy conservation, such as use of methane gas generated in anaerobic digestion of sludge. The USEPA has already begun work on a new set of criteria to be used by construction grant review boards at both the state and federal level. Municipalities applying for federal assistance in construction of sewage facilities will be required to submit alternative proposals, each of which must characterize the primary energy required to run the plant plus the indirect energy requirements consumed as chemicals, filter media, and other materials. These proposals should ensure an appropriate weighting of both operating and maintenance requirements and initial capital costs.

The energy requirements for three irrigation areas are estimated in this report. Each of the areas—Kern County, California, the Texas high plains, and San Carlos, Arizona—is located in the arid Southwest and extracts at least a portion of its water requirement from groundwater supplies. Based on the energy requirements projected for these three locations between 1977 and 2000, the growth in the energy required to supply water for irrigation will not exceed the growth in national energy consumption during this period. These areas, however, would exhibit a more significant growth in the energy required to supply irrigation water if agricultural production were to increase or even to be maintained, as in the case of the Texas high plains, where acreage is presently being withdrawn from production. Even so, the energy requirements to supply water for irrigation are not a short-term problem because neither the pattern of agricultural production nor the mechanism of water supply presently in use is expected to change dramatically before the end of the century. After the year 2000, however, groundwater depletion or degradation of water quality may necessitate systems in some areas of the Southwest if the United States is to retain its global role as a major food producer. New water supplies from desalination, interbasin transfer, or water reuse will consume significantly more energy than is presently necessary to obtain water for irrigation. A careful examination of the trade-offs among energy consumption, water consumption, and food production is important in assessment of long-range water-supply alternatives. The financial productivity of water in its competing uses should be calculated, but these calculations should be supplemented with estimates of public or social costs and benefits before such estimates are used to guide policy decisions. Attention must be given to the costs incurred in other geographical areas or in other economic sectors when additional water supplies are diverted to or from agriculture.

The results of this study indicate that (in the absence of severe drought) before the year 2000 energy requirements for water supply and water treatment will most likely be met without major problems. Additional analysis of the long-term options for water supply in the arid Southwest and for sewage treatment throughout the United States should be undertaken, however, if the nation is to successfully meet both the demand for energy and the demand for water after the year 2000. Regional planning and multipurpose construction of water systems should be emphasized in these studies. In addition, alternatives should be compared on the basis of comprehensive cost-benefit analysis in which the political, economic, geographic, environmental, and social variables that influence water consumption and its associated energy requirements are simultaneously considered. The energy requirement for water supply and water treatment is exceedingly important because it reflects ways in which our physical environment is affected in maintenance of water systems, but it is only one of many important factors that must be considered in the attempt to ensure efficient allocation of resources.

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ABBREVIATIONS

AS	activated sludge
AWT	advanced wastewater treatment
FEA	Federal Energy Administration
Filt	filtration
mgd	million gallons daily
mil gal	million gallons
MJ	megajoule
MJ/mil gal/ft	megajoules required to lift one million gallons one foot
Nitr	nitrification
TF	trickling filter
USEPA	United States Environmental Protection Agency

APPENDIX 1

WATER SUPPLY SURVEY FORM

DATA FORM
WATER SUPPLY SYSTEM

1. Present source(s) of water supply and percentage of total supply:

Source	% of Total Supply

2. Please give a brief description of the treatment process you employ (i.e. sequence of treatment units used in process).

3. We would appreciate it if you could supply us with the following historical data. As we explained in our letter, this data is essential for us to determine trends and to make projections. We have divided the data by sources: surface and ground. Please note the different years requested in each table. If your community uses ground water and if ground water records are readily available, we would be interested in knowing the depth to ground water not only for the years listed on the form, but also for the years prior to 1950 (in five year intervals).

Surface Water Supply

Survey of Energy Requirements to Supply Water Over Time

	1950	1965	1966	1967	1968	1969
PERCENTAGE OF TOTAL SUPPLY:						
POPULATION SERVED:						
AVERAGE DAILY FLOW (MGD)- Withdrawals:						
Loss (e.g. backwashing):						
Net Supply:						
ENERGY- ENERGY CONSUMED IN TREATMENT PROCESS- Electricity- Purchased:						
On-Site:						
Natural Gas:						
Fuel Oil:						
Coal:						
ENERGY CONSUMED IN DISTRIBUTION- Electricity- Purchased:						
On-Site:						
Other:						
TOTAL AMNT. OF ENERGY CONSUMED BY SYSTEM- Electricity- Purchased:						
On-Site:						
Natural Gas:						
Fuel Oil:						
Coal:						
DISTRIBUTION- (Average distance treated water is transported):						

Surface Water Supply

Survey of Energy Requirements to Supply Water Over Time

	1970	1971	1972	1973	1974	1975	1976
PERCENTAGE OF TOTAL SUPPLY:							
POPULATION SERVED:							
AVERAGE DAILY FLOW (MGD)- Withdrawals:							
Loss (e.g. backwashing):							
Net Supply:							
ENERGY- ENERGY CONSUMED IN TREATMENT PROCESS- Electricity- Purchased:							
On-Site:							
Natural Gas:							
Fuel Oil:							
Coal:							
ENERGY CONSUMED IN DISTRIBUTION- Electricity- Purchased:							
On-Site:							
Other:							
TOTAL AMNT. OF ENERGY CONSUMED BY SYSTEM- Electricity- Purchased:							
On-Site:							
Natural Gas:							
Fuel Oil:							
Coal:							
DISTRIBUTION- (Average distance treated water is transported):							

Groundwater Supply

Survey of Energy Requirements to Supply Water Over Time

	1950	1955	1960	1965	1970
PERCENTAGE OF TOTAL SUPPLY:					
POPULATION SERVED:					
AVERAGE DAILY FLOW (MGD)-					
Withdrawals:					
Loss (e.g. aquifer recharge):					
Net Supply:					
ENERGY CONSUMED IN PUMPING-					
Electricity- Purchased:					
On-Site:					
Other:					
ENERGY CONSUMED IN TREATMENT PROCESS-					
Electricity- Purchased:					
On-Site:					
Natural Gas:					
Fuel Oil:					
Coal:					
ENERGY CONSUMED IN DISTRIBUTION-					
Electricity- Purchased:					
On-Site:					
Other:					
TOTAL AMNT. OF ENERGY CONSUMED BY SYSTEM-					
Electricity- Purchased:					
On-Site:					
Natural Gas:					
Fuel Oil:					
Coal:					
DISTRIBUTION- (Average distance treated water is transported):					
AVERAGE DEPTH TO GROUND WATER:					

Groundwater Supply

Survey of Energy Requirements to Supply Water Over Time

	1971	1972	1973	1974	1975	1976
PERCENTAGE OF TOTAL SUPPLY:						
POPULATION SERVED:						
AVERAGE DAILY FLOW (MGD)- Withdrawals:						
Loss (e.g. aquifer recharge):						
Net Supply:						
ENERGY CONSUMED IN PUMPING- Electricity- Purchased:						
On-Site:						
Other:						
ENERGY CONSUMED IN TREATMENT PROCESS- Electricity- Purchased:						
On-Site:						
Natural Gas:						
Fuel Oil:						
Coal:						
ENERGY CONSUMED IN DISTRIBUTION- Electricity- Purchased:						
On-Site:						
Other:						
TOTAL AMNT. OF ENERGY CONSUMED BY SYSTEM- Electricity- Purchased:						
On-Site:						
Natural Gas:						
Fuel Oil:						
Coal:						
DISTRIBUTION- (Average distance treated water is transported):						
AVERAGE DEPTH TO GROUND WATER:						

4. Will your present sources of supply meet demands in 1980? ____Yes ____No

in 1990? ____Yes ____No

in 2000? ____Yes ____No

5. If present sources will be inadequate to meet future demands, what additional or alternative sources are you considering?

6. What is the projected population to be served by your system in the following years?

Year	Projected Population to be Served
1980	
1990	
2000	

APPENDIX 2

Primary and Secondary Energy Requirements for Drilling Wells

M. Woo, in his recently completed study, "Energy and Material Requirements of Crude Oil Production," uses the 1972 Census of Manufactures, SIC 13818-01 "Drilling Oil, Gas, Dry, Service Wells," to calculate the primary and secondary energy required to drill wells. His estimate indicates that 565 MJ are required per foot drilled. We take this value as our (approximate) average of the energy required in drilling wells for water supply.