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Assessment of Water Resources for Nuclear Energy Centers

G. Samuels

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ENERGY DIVISION

ASSESSMENT OF WATER RESOURCES FOR NUCLEAR ENERGY CENTERS

G. Samuels

SEPTEMBER 1976

This study was performed for the Nuclear Regulatory Commission in connection with the development of their Nuclear Energy Center Site Survey report to Congress.

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Oak Ridge, Tennessee 37830
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FOREWORD

Section 207 of the Energy Reorganization Act of 1974 required the Nuclear Regulatory Commission to conduct a nuclear energy center site survey and report its findings to the Congress and the Council of Environmental Quality. The Survey included a general screening of the 48 contiguous States to identify large land areas that would be likely to contain sites potentially suitable for nuclear energy centers. It evaluated the technical and practical considerations involved in locating the production of electric power at a nuclear energy center and compared these considerations with those involved in producing an equivalent amount of power at dispersed sites.

This account of the assessment of water resources for nuclear energy centers has been developed as part of the technical basis for the coarse screening criterion used by the U.S. NRC in preparation of the NECSS-75 Report to Congress. Neither this account nor the criteria used in the NECSS Report represent a considered judgment of the actual availability of water or the environmental impact of a specific center which might be proposed. Rather, the data presented herein represent an overview of the scope of problems and interactions which might be encountered should circumstances dictate a deeper examination of the feasibility and practicality of a specific nuclear energy center.

ABSTRACT

Maps of the conterminous United States showing the rivers with sufficient flow to be of interest as potential sites for nuclear energy centers are presented. These maps show the rivers with (1) mean annual flows greater than 3000 cfs, with the flow rates identified for ranges of 3000 to 6000, 6000 to 12,000, 12,000 to 24,000, and greater than 24,000 cfs; (2) monthly, 20-year low flows greater than 1500 cfs, with the flow rates identified for ranges of 1500 to 3000, 3000 to 6000, 6000 to 12,000, and greater than 12,000 cfs; and (3) annual, 20-year low flows greater than 1500 cfs, with the flow rates identified for ranges of 1500 to 3000, 3000 to 6000, 6000 to 12,000, and greater than 12,000 cfs.

Criteria relating river flow rates required for various size generating stations both for sites located on reservoirs and for sites without local storage of cooling water are discussed. These criteria are used in conjunction with plant water consumption rates (based on both instantaneous peak and annual average usage rates) to estimate the installed generating capacity that may be located at one site or within a river basin.

Projections of future power capacity requirements, future demand for water (both withdrawals and consumption), and regions of expected water shortages are also presented.

Regional maps of water availability, based on annual, 20-year low flows, are also shown. The feasibility of locating large energy centers in these regions is discussed.

ASSESSMENT OF WATER RESOURCES FOR NUCLEAR ENERGY CENTERS

1. INTRODUCTION

The purpose of this report is to discuss water supply vs requirements for the United States, with a view toward identifying areas that have potential water resources sufficient to support nuclear energy centers (NECs).¹ This report does not discuss social or institutional restraints on, or national priorities for, the use of water or the development of water resources. There are areas of the United States that have, or are projected to have, serious water supply problems, and these areas are identified. The approach taken is to compile information on water resources as they currently exist, from which those areas with sufficient water to warrant further evaluation are mapped.

Although NECs are defined as installations of 10 or more reactors, the water resource maps of this section also show those rivers with sufficient flow to be of interest for smaller 5- to 10-unit power stations. The reason for including the rivers with lower flows is that water may be pumped some distance to supply an NEC. Thus, two rivers within a short distance of each other, each with sufficient flow to support 5 units, could be used to supply a 10-unit NEC. Also, the inclusion of rivers with lower flows gives insight as to the additional areas that may be available for a smaller power complex.

To perform a survey of possible NEC sites, it is first necessary to establish criteria or guidelines for the NEC requirements and for the necessary resources to meet these requirements. The water requirements for an NEC will depend on the type of cooling system used, which for this survey is assumed to be wet cooling towers. It is also assumed that the cooling water is drawn from local surface waters and that some percentage of this intake is returned as blowdown from the NEC cooling system.

The water demand for a power plant cooling system can be expressed as a withdrawal rate (the quantity taken from local sources) or as the consumptive use, which in this case is the quantity evaporated in the cooling towers. The difference between these quantities is the blowdown

from the system. Drift losses from the tower, although possibly important from the viewpoint of local environmental effects, have a negligible effect on water requirements. The ratio of the withdrawal rate to the blowdown rate is the concentration ratio, or the multiple to which the impurities in the intake water are concentrated before being discharged from the cooling system.

The consumptive use, in this case the water evaporated by the cooling system, represents the demand placed on local water resources. The concentration ratio has essentially no effect on the amount of water used. However, this ratio will affect the heat added to local surface water and, depending on the cooling water system treatment within the plant, may affect the level of impurities in the water. Both of these are discussed later.

The assumed use of wet cooling towers results in a greater evaporative use of cooling water (about 40% greater) than once-through systems. The difference in the evaporation rate between the two systems is caused by the higher temperature at which the cooling takes place in a cooling tower. This higher temperature, and thus high water vapor pressure, increases the ratio of the amount of heat transferred by evaporation to that transferred as sensible heat.

As an aid to the reader, the definition of some of the more commonly used hydrologic terms and conversion tables for units of volume and flow are given in the Appendix.

2. CONSUMPTIVE WATER USE

The quantity of water evaporated to reject a given amount of heat in a wet cooling tower will depend on the wet- and dry-bulb temperatures and the water temperature to and from the cooling tower. Thus, the water demand will vary seasonally and from one location to another. The water demand will be highest during hot weather, when air and thus cooling water temperatures are highest. In most parts of the country having adequate fresh water resources for an NEC, about 80 to 85% of the heat is rejected by evaporation of the cooling water during warm weather, and the remaining 15 to 20% goes to raising the temperature of the air drawn through the cooling tower. If it is assumed that this split of heat rejection is 85% by evaporation and 15% to the air and that the average water temperature in the cooling tower is 100°F (latent heat of evaporation, 1037 Btu/lb), the total heat rejected for each pound of water evaporated is $1037/0.85$, or 1220 Btu. The amount of water evaporation for each kilowatt of power generated depends on the efficiency of the power plant, which for water reactors is about 1/3. Thus, for each kilowatt generated, 2 kW (6826 Btu/hr) of heat must be rejected. This requires the evaporation of 5.60 lb of water for each kilowatt-hour of electricity, which implies that a typical 1200-MWe water reactor will consume a maximum of about 6,720,000 lb of water per hour (equivalent to about 30 cfs). In actual operation, some small part of the heat (1 to 3%) will be rejected by the blowdown from the plant. An NEC of from ten to forty 1200-MWe reactors would consume from 300 to 1200 cfs of water by evaporation. These water use rates are for warm-weather conditions. During cold weather, a larger percentage of the heat is given to the air, and the water consumption rate will be less (about 75 to 85% of the summer consumption rate in most parts of the United States).

Typical performance curves for a natural-draft cooling tower are given in Fig. 1 for a range (water temperature change in passing through the cooling tower) of 30°F and an ambient air relative humidity of 70%. The air dry-bulb temperature is shown for reference purposes and is determined by the air wet-bulb temperature and the relative humidity. The cooling tower operating conditions are primarily determined by the

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Fig. 1. Typical natural-draft cooling tower performance.

wet-bulb temperature, with some smaller influence by the dry-bulb temperature. The upper curve of Fig. 1 shows the variation of the percent of the heat rejected by evaporation as a function of the wet-bulb temperature for the assumed range and relative humidity. The water temperature off the tower is the temperature to which the water is cooled in passing through the tower. The difference between the water temperature off the tower and the wet-bulb temperature is the tower approach.

Design air temperatures vary widely across the country, and the relative humidity of 70% used in Fig. 1 is representative of peak summer conditions, averaged over a 24-hr period, in the eastern part of the country. Typical summer day design dry-bulb temperatures range between the upper 80's and upper 90's. Design wet-bulb temperatures are usually in the 70's, and the relative humidity is about 50%. The day-to-night dry-bulb temperature change is about 20°F, and with a constant air moisture content, the wet-bulb temperature decreases about 5°F and the relative humidity increases to about 90%. Thus, peak 24-hr summer conditions are a wet-bulb temperature in the low 70's, a relative humidity of about 70%, and a corresponding dry-bulb temperature of about 80°F. About 85 or 86% of the heat is rejected by evaporation for these conditions. For very hot arid areas, the percentage of heat rejected by evaporation is somewhat greater, while for more humid conditions or for cold weather, the heat rejected by evaporation, is less.

The water temperature off the tower (Fig. 1) shows a trend that can cause thermal discharge problems during winter operation. As the air temperature decreases, the water temperature, which is also the temperature of the plant blowdown stream, decreases, but at a slower rate. The river temperature also follows the air temperature, and as the tower approach increases, so does the temperature difference between the blowdown stream and the river. Furthermore, the cooling tower responds to air changes much more rapidly than the river. A sudden air temperature increase can lead to a rather large difference between the temperatures of the blowdown stream and the river and can cause a significant increase in the river temperature. This is discussed in detail in the following section.

3. THERMAL DISCHARGE

The thermal discharge or heat rejected to local surface waters with a cooling tower system depends on the concentration ratio and is on the order of 1 to 3% of that typical of once-through run-of-river cooling. As noted previously, the concentration ratio R is equal to the withdrawal rate W divided by the blowdown rate B , while the evaporation rate E is the difference between the withdrawal and blowdown rate. Thus,

$$E = W - B ,$$

$$R = W/B ,$$

and by substitution,

$$E = RB - B = B(R - 1) ,$$

or

$$B = E/(R - 1) .$$

The rate of heat rejection by the blowdown, Q_b , is equal to the product of the blowdown rate, the heat capacity, C_p , and the temperature difference, ΔT_b , between the blowdown and the local water source. Thus,

$$Q_b = BC_p \Delta T_b ,$$

and

$$Q_b = EC_p \Delta T_b / (R - 1) .$$

Using a value of E equal to 5.6 lb/hr for each kilowatt of electricity generated, Q_b can be expressed in dimensionless form, Q_r , as the ratio of heat rejected to the power generated:

$$Q_r = 0.00164 \Delta T_b / (R - 1) ,$$

when ΔT_b is in degrees Fahrenheit. A graph of this equation is shown in Fig. 2. Another manner in which the thermal effects of blowdown can be expressed is the effect on the temperature of the receiving body of water. If the local water source is a river, then the temperature rise in the river can be expressed as a function of the fraction of the river flow that is evaporated, the concentration ratio, and the temperature difference between the blowdown flow and the river. If the river flow rate is S and the increase in the average river temperature caused by the blowdown is ΔT_s (assuming instantaneous mixing at the point of blowdown entry), then a heat balance gives

$$(S - E)\Delta T_s = B \Delta T_b = E \Delta T_b / (R - 1) ,$$

or

$$\Delta T_s / \Delta T_b = \frac{E}{(S - E)(R - 1)} = \frac{E/S}{(1 - E/S)(R - 1)} ,$$

where E/S is the fraction of the river flow evaporated and $\Delta T_s / \Delta T_b$ is the ratio of the river temperature rise to the blowdown temperature rise. A graph of this equation is shown in Fig. 3. The critical period for increases in the river temperature will be during relatively warm humid periods during the winter or early spring, when the river is cold. The blowdown ΔT_b during this time may be as high as 40°F, and if the limit on the increase in river temperature is 4°F, then a cooling system with a concentration ratio of 2 would be limited to an evaporation rate of about 9% of the river flow rate. During the summer and early fall, the value of ΔT_b will usually be smaller; however, limitations on the maximum allowable river temperature, rather than the increase in river temperature, may be a restriction. Thus, even with a wet cooling tower, the thermal discharge from the NEC may restrict the amount of water that can be used.

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Fig. 2. Heat rejection rate as a function of the concentration ratio and the temperature difference between the blowdown and the local water source.

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Fig. 3. Ratio of river temperature rise to blowdown temperature rise as a function of the fraction of the river flow evaporated and the concentration ratio.

4. WATER QUALITY

Water quality must be evaluated for its intended use. For use in cooling towers, one is most concerned with the dissolved solids, especially those affecting the hardness of the water, and the suspended solids. Because of the wide variability of water quality for cooling purposes throughout the country (as shown in Figs. 4 and 5)² and the variety of treatment methods available, the problems associated with water quality and treatment are site-dependent. Furthermore, the effect of an NEC on the water quality for other purposes is also difficult to generalize and requires site-specific data.

If the river water is used in the plant cooling system without treatment, that is, without addition of chemicals or elimination of naturally occurring impurities, then the concentration ratio is a direct measure of the degree to which the impurities are concentrated in the blowdown. However, the concentration ratio has no effect on the total quantity of impurities in the river downstream from the point of blowdown return. Because the total quantity of impurities is the same downstream as at the point of water withdrawal, the increase in the concentration (outside of a local mixing zone) is proportional to the decrease in the river flow, and the decreased flow depends almost totally on the evaporation rate. For cooling systems without blowdown, where all of the water withdrawn is evaporated on site, the concentration of impurities is unchanged. However, the water consumed by the plant may have an adverse effect on downstream quality because of the reduced flow available to dilute wastes added to the river. In current practice, practically all evaporative cooling systems use blowdown and some form of chemical treatment. The cooling system concentration ratio depends on the local water quality and the water treatment used and should be evaluated on a site-by-site basis.

Much of the current concern about water quality involves the addition of wastes to rivers and the effect of these wastes on the oxygen content of the water. As noted by Burwell,³ cooling towers are effective water aerators and will be beneficial in this respect. A detailed study of current and projected water quality problems in the United States is given by Wollman and Bonem⁴ and is discussed later.

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Fig. 4. Concentration of dissolved solids in streamflow. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

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Fig. 5. Concentration of sediment in streams. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

5. WATER RESOURCES AND PROJECTED DEMAND

The primary purpose of this section is to review background information useful in deriving a set of guidelines that will enable one to determine (1) the quantity of flow needed as a water source for an NEC; (2) whether, and when, storage of water is required; and (3), if storage is required, the amount needed. The answers to these questions will depend on the quantity and dependability of local water resources and the fraction of these resources that can be used for the NEC.

5.1 Water Resources

To arrive at a set of guidelines, a considerable amount of background information concerning water resources must be understood, and the ecological, as well as other, effects of drawing on these resources must be evaluated. There is a wealth of information available on water resources in the United States, and a review of some of the more basic information and other considerations affecting design guidelines is given below.

As a whole, the United States has abundant water resources, having an annual average precipitation of 30 in. for the conterminous United States and an average natural runoff of 1200 billion gallons per day (equivalent to 1,860,000 cfs). However, these resources are not uniformly distributed, as the annual precipitation ranges from a low of about 4 in. in the Great Basin and lower Colorado regions to over 100 in. in coastal areas of the Columbia-North Pacific region (see Fig. 6). Water problems in the more arid regions of the country are made even more severe by high evaporation and potential evapotranspiration losses. Potential evapotranspiration is defined as the evapotranspiration that would occur if an adequate supply of water were available at all times and, for practical purposes, may be assumed to be nearly equal to evaporation from a free water surface as shown in Fig. 7.²

Areas of the country in which a water surplus or deficiency commonly exists are shown in Fig. 8.² The values shown were determined by subtracting the potential evapotranspiration rate from the average annual

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Fig. 6. Average annual precipitation. Source: U.S. Water Resources Council, The Nation's Water Resources, U.S. Government Printing Office, Washington, D.C., 1968.

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Fig. 7. Average annual lake evaporation. Source: U.S. Water Resources Council, The Nation's Water Resources, U.S. Government Printing Office, Washington, D.C., 1968.

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Fig. 8. Areas of natural water surplus and natural water deficiency. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

precipitation. However, even in areas normally having a water surplus, there are often seasonal or short-term periods of deficiency.

Inland NEC sites, depending on fresh water for cooling, will be located near large rivers or the Great Lakes. The availability of water at any location along a river depends on the size of the upstream drainage area of the river basin, surface water runoff for the drainage area, and upstream consumptive use or other losses. The drainage areas of the various major river basins and their tributaries are well documented in the U.S. Geological Survey (USGS) publications, as are their surface water runoffs (see Fig. 9). A rather simple relation between the mean annual flow in a river, neglecting upstream uses and losses, and the runoff and drainage area is as follows: The flow from a river basin is 0.074 cfs per square mile of drainage area for each inch of annual runoff. Conversely, it requires an average runoff of about 13.6 in. for a river to have a flow of 1 cfs per square mile of drainage area, a value that is typical of many rivers in the eastern half of the United States.

In addition to the mean annual flow, the annual and seasonal variations in flow must be considered in any site selection process. The variability of annual runoff for the various water resources regions (see Fig. 10 for a map of these regions) is shown in Fig. 11. In the one driest year out of 20, the annual natural runoff will be equal to or less than the indicated percent of the mean. Seasonal flows also vary widely throughout the United States, not only as to quantity, but also as to the season in which high and low flows occur. Figure 12 shows the seasons of low flow for the United States.⁵ The numbers shown in the figure represent the month in which the low flow normally occurs (1 for January, 2 for February, etc.). Caution must be exercised in interpreting annual runoff or historical data on river flows because of changes that have been made to the river basins during the period in which the data were accumulated. Even the annual runoffs can be influenced by upstream reservoirs because many of these have storage capacities greater than their annual throughflow. Data and analytical techniques are available to predict flow variations, which can be applied on a site-by-site basis. In consideration of the very large investment in an NEC, criteria

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Fig. 9. Average annual runoff. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

Fig. 10. Water resources regions. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

1 Does not include runoff from Canada

2 Does not include runoff derived from upstream regions

3 Does not include runoff from Mexico

Fig. 11. Variability in annual natural runoff. In the 1 driest year out of 20, the annual natural runoff will be equal to or less than the indicated percent of the mean. Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

Fig. 12. Seasons of lowest flows. Source: U.S. Department of Agriculture, *The Yearbook of Agriculture 1955: Water*, U.S. Government Printing Office, Washington, D.C.

used as a basis for identifying potential sites should be chosen to ensure a high probability that adequate cooling water supplies will be available during the center's long operating life.

5.2 Demand Projections

A summary of projected withdrawals and consumptive uses of water for different purposes is given in Table 1 for the United States, and a projection of total withdrawals and consumptive uses for the various water resource regions is given in Table 2.² These projections are based on greater efficiency of water use. Furthermore, the withdrawals estimated for year 2020 in relation to the runoff indicate a large increase in water reuse and thus a need for increased investment in water development, water conditioning, waste treatment, and water management to meet the estimated requirements.

Figure 13 shows projected fresh water withdrawals and consumptive uses as a percent of the estimated supply. The 100 shown on each of the graphs represents the estimated average supply. The significance of these projections and precautions in interpreting the figure are taken directly from Ref. 2 and are quoted below:

In interpreting Fig. [13], attention must be given to the following points: (1) the water use figures include use of mined groundwater, which is particularly prevalent in southwestern regions and cannot continue indefinitely; (2) the water use requirements include some saline withdrawals by self-supplied industries; (3) the water use figures do not include phreatophyte and other channel losses which are particularly important in the arid regions; (4) the water use data do not include requirements for instream uses; and (5) the data do not reflect seasonal variations or within-region locational aspects of supply-use comparisons.

When the regional withdrawal index is 100, the region is withdrawing an amount of water equal to the estimated supply (Fig. [13]). Since these withdrawals are not located at one point in the region, some parts will be reusing return flows of upstream withdrawals. The withdrawal index gives an indication of water management and pollution control problems, but not necessarily of water shortage.

The regional consumptive use index on the other hand does give an indication of water shortage. When the existing or projected index is 50, the region would be

Table 1. Estimated water use and projected requirements, by purpose, United States
(in Mgd)

Type of use	Withdrawals				Consumptive use			
	Used 1965	Projected requirements			Used 1965	Projected requirements		
		1980	2000	2020		1980	2000	2020
Rural domestic	2,351	2,474	2,852	3,334	1,636	1,792	2,102	2,481
Municipal (public-supplied)	23,745	33,596	50,724	74,256	5,244	10,581	16,478	24,643
Industrial (self-supplied)	46,405	75,026	127,365	210,767	3,764	6,126	10,011	15,619
Steam-electric power								
Fresh	62,738	133,963	259,208	410,553	659	1,685	4,552	8,002
Saline	21,800	59,340	211,240	503,540	157	498	2,022	5,183
Agriculture								
Irrigation	110,852	135,852	149,824	160,978	64,696	81,559	89,964	96,919
Livestock	1,726	2,375	3,397	4,660	1,626	2,177	3,077	4,238
Total	269,617	442,626	804,610	1,368,088	77,782	104,418	128,206	157,085

Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

Table 2. Estimated water use and projected requirements, by regions, United States
(in Mgd)

Region	Withdrawals				Consumptive use			
	Used 1965	Projected requirements			Used 1965	Projected requirements		
		1980	2000	2020		1980	2000	2020
North Atlantic	37,467	54,920	113,860	236,290	2,023	2,870	4,960	8,490
South Atlantic-Gulf	20,560	53,180	87,440	130,190	2,695	3,395	5,655	8,265
Great Lakes	25,119	47,893	96,594	190,960	1,199	1,881	3,183	5,484
Ohio	28,255	41,749	65,109	90,163	1,134	1,619	2,539	3,623
Tennessee	5,767	12,252	13,877	18,106	331	572	834	1,132
Upper Mississippi	8,179	14,800	30,587	41,266	770	1,103	1,778	2,624
Lower Mississippi	5,571	12,816	27,967	39,442	1,470	3,012	4,453	6,251
Souris-Red-Rainy	391	936	2,002	2,758	11	215	494	544
Missouri	19,344	23,264	27,876	31,572	10,554	13,160	14,979	16,378
Arkansas-White-Red	9,410	17,279	25,336	31,589	5,874	8,482	10,587	12,329
Texas-Gulf	16,410	29,080	57,330	92,640	7,289	9,435	10,890	12,300
Rio Grande	7,289	8,330	9,510	11,680	4,403	4,676	4,991	5,466
Upper Colorado	4,017	5,675	6,575	6,725	1,982	2,700	3,100	3,140
Lower Colorado	6,913	8,497	8,428	8,889	3,448	4,075	4,645	5,310
Great Basin	5,115	7,055	7,550	7,800	2,253	3,299	3,562	3,776
Columbia-North								
Pacific	29,631	41,407	90,135	156,735	10,521	13,581	17,325	21,616
California	37,300	56,290	120,510	244,760	20,944	29,205	32,660	38,190
Alaska	162	535	901	4,206	12	50	96	184
Hawaii	1,597	2,658	4,698	8,587	533	728	1,000	1,368
Puerto Rico	1,120	4,010	8,325	13,730	270	360	475	615
Total	269,617	442,626	804,610	1,368,088	77,782	104,418	128,206	157,085

Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

Fig. 13. Regional indices of projected water withdrawals and consumptive uses, 1965-2020 (estimated average supply equals 100). Source: U.S. Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.

consuming 50% of the available supply. The consumptive use index understates the water shortage problem because account has not been taken of seasonal shortages. Also, the regional indices are based on averages for large regions and cover up the seriousness of water-shortage problems in local areas.

There are many local areas in all parts of the country where shortage of water restrains economic activity, but these areas cannot be identified with the general approaches used in this analysis. Even with this limited analysis, however, the Council has identified several regions in which existing water resources are now inadequate or over the next 50 years will not sustain the patterns and rates of growth experienced in recent years and projected over the next 50. The effect of water shortages, unless counter measures are taken, will be an adjustment in the pattern of economic activities. In some cases it may mean a slowdown in the rate of increase in total economic activity in the region.

In view of the present and projected inadequacy over the next 50 years of the water supplies available to meet requirements in several regions, the Council finds that alternative means of alleviating such water shortages and the national interest therein should be identified and considered. Any study of such alternative means should include consideration of transfer of water between basins, interstate and international terms and conditions of such possible transfers, protection of areas of origin, economic alternatives available to the areas of need, and the national interest in both areas of origin and need.

In a later study⁶ of water resources and their relationship to energy self-sufficiency, the Water Resources Council (WRC) identified several areas of the country that may have critical water-related problems in 1985. These areas are shown in Fig. 14. There appears to be some question as to the rate of growth in energy-related water requirements used in this study; however, these growth projections primarily affect the timing of the shortages (i.e., a critical supply in 1985 or in 2000) rather than the basic conclusions. A summary of the problems associated with the critical areas is quoted from Ref. 6 in the following two paragraphs:

The most severe water supply problem in the Eastern critical regions is associated with fresh water consumptive use for cooling of electric power generation facilities, related thermal and refinery pollution problems and the incompatibility of development with the desire for return

Fig. 14. Geographic areas with critical water-related energy problems. Source: U.S. Water Resources Council, *Project Independence, Water Requirements, Availabilities, Constraints, and Recommended Federal Actions*, U.S. Government Printing Office, Washington, D.C., November 1974.

to or maintenance of a natural environment held by a large vocal segment of the population. The solution to this problem lies in giving proper attention to environmental and social concerns as well as utilizing, wherever possible, saline offshore waters for cooling purposes.

The most severe water supply problem in the Western regions is associated with fresh water consumptive use and salinity problems for mining and processing of the oil shales and coal reserves currently planned to be exploited. The most significant constraint related to this problem is of an institutional nature (water rights) and must be resolved before significant increases in consumptive use for energy development can be accommodated. The solution to this problem is very complex and will require major State/Federal actions which are mutually acceptable to both parties.

Wollman and Bonem,⁴ in their book *The Outlook for Water*, present a detailed study of water supply and requirements; they project future water demand on the basis of maintaining adequate water quality (a minimum of 4 mg of dissolved oxygen per liter). Their approach, basing the required flow on that necessary for the dilution of industrial and municipal wastes, gives a detailed economic analysis which considers the cost of both waste treatment and the reservoirs for augmenting low stream flows. The study emphasizes the need for large expenditures for waste treatment facilities to reduce waste loads and for reservoirs to improve stream flow regulation. This is illustrated in Table 3, which shows the 1964 and maximum attainable flow and projections of demands by region through 2020. The demands are based on medium projections of population and economic activity and their "minimum flow" case, which assumes a 97.5% biochemical oxygen demand removal from both industrial and municipal wastes (tertiary treatment). Both regulated flow conditions are based on a reliability of 98%. The 98% reliability is defined as the probability of the flow shown being available (at all times during the year) for all but 2 years in each 100 years. The maximum regulated flow is defined as the maximum flow that can be attained with reservoirs regardless of cost, that is, no restriction on the cost of the added flow.

In Table 3, the required flows that exceed the present regulated flow for a specific region are shown in parentheses, and the required

Table 3. Present and maximum regulated flow and total required flow (in Mgd)

Region	Regulated flow		Required flow (medium) ^a		
	Present	Maximum	1980	2000	2020
New England	22,400	60,895	3,177	4,522	6,474
Delaware and Hudson	7,500	28,629	6,486	(9,785)	(14,627)
Chesapeake Bay	3,400	46,657	(6,025)	(10,410)	(17,767)
Ohio	10,000	99,457	4,154	6,748	(11,055)
Eastern Great Lakes	3,500	33,278	(4,800)	(7,995)	(13,482)
Western Great Lakes	8,800	30,283	(10,639)	(17,502)	<u>30,641</u>
Upper Mississippi	15,800	46,125	3,350	5,321	<u>8,275</u>
Lower Missouri	5,400	16,211	957	1,657	2,896
Southeast	95,000	186,030	25,451	48,176	87,941
Cumberland	11,100	14,647	1,810	4,280	9,088
Tennessee	20,800	40,389	3,019	5,742	10,381
Lower Mississippi	1,500	35,207	(3,130)	(5,311)	(8,536)
Lower Arkansas-White-Red	23,900	57,661	3,099	4,463	6,064
Upper Missouri	25,600	25,600	15,912	18,179	24,084
Upper Arkansas-White-Red	6,700	7,053	(6,730)	<u>7,486</u>	<u>8,969</u>
Western Gulf	15,400	25,900	(17,235)	<u>26,747</u>	<u>44,441</u>
Upper Rio Grande-Pecos	3,000	3,000	<u>5,507</u>	<u>6,529</u>	<u>8,921</u>
Colorado	11,400	11,400	<u>16,950</u>	<u>25,204</u>	<u>42,643</u>
Great Basin	5,400	6,934	(6,251)	<u>7,011</u>	<u>10,046</u>
South Pacific	700	815	8,135	<u>12,278</u>	<u>18,055</u>
Central Pacific	26,200	45,478	(26,834)	(30,309)	(37,267)
Pacific Northwest	62,800	134,570	25,068	36,886	58,005
United States	386,300	956,219	204,719	302,541	479,658

^a Parentheses indicate projected requirements exceed present regulated flows; underlining indicates projected requirements exceed maximum regulated flows.

flows that exceed the maximum regulated flow are underlined. The total present and maximum potential regulated flows for the United States are 386 and 956 billion gallons per day (bgd). The Water Resources Council (WRC)⁶ gives values for current and potential surface supply, with a 98% confidence, of about 300 and 800 bgd. The WRC current supply of 300 bgd is based on the assumption that only 50% of the current reservoir capacity is used to improve low flow conditions; whether or not restrictions were placed on the potential supply is not stated. Considering that the average runoff from the United States is about 1200 bgd and that the low runoff in one year out of 20 is about 700 bgd, a flow of either 800 or 956 bgd, with a confidence level of 98%, will require an enormous reservoir system, most of which must be built.

The difficulty of maintaining a dissolved oxygen level of 4 mg/liter is further emphasized by consideration of the EPA-proposed criteria for water quality.⁷ The section of the EPA report for dissolved oxygen states:

(1) Minimum acceptable limits of dissolved oxygen for all water shall be based upon seasonal temperatures. Minimum acceptable limits are presented in the table below:

°C	Oxygen levels for complete saturation (mg/liter)	Minimal levels for protection of salmonid spawning (mg/liter)	Minimal levels for protection of aquatic life (mg/liter)
36	7	6.4	5.8
27.5	8	7.1	5.8
21	9	7.7	6.2
16	10	8.2	6.5
7.7	12	8.9	6.8
1.5	14	9.3	6.8

(2) As an exception, under extreme conditions for short periods of not more than 24 hours, a minimum limit of 4 mg/l is acceptable for waters above 31°C (87.8°F).

It is not the intent of this report to discuss national or industrial priorities for water use. However, the value of water for power plant cooling purposes is high if the alternative is the use of dry cooling towers. A comparison of power generating costs (derived from Ref. 8) shows the power cost for a plant with dry towers to be 1.63 mills/kWhr greater than for a plant with wet towers. For a 1200-MWe plant, this is about \$2000/hr. The consumptive use of water for the plant is between 2.0 and 2.5 acre-ft/hr. Thus, the value of water for this comparison is about \$800 to \$1000/acre-ft and is far greater than the value of water for irrigation of field crops.

6. RESERVOIR CONSIDERATIONS

For those NEC sites that require storage of water for periods when the flow available from adjacent sources is insufficient, losses (evaporation and percolation) from the reservoir must be considered. Especially, evaporation and percolation losses will increase the demand on local water resources in arid regions, where evapotranspiration losses are normally low. In sizing the reservoir, the net loss (or gain), which is the difference between the evaporation (Fig. 7) and percolation loss and the local precipitation (Fig. 6), should be used. However, the evaporation rate will be highest during the summer or early fall when the reservoir is probably most needed.

The reservoir capacity required will depend on the individual river flow characteristics, water demand, and reservoir losses and must be evaluated for each specific site. For most locations, a useful storage capacity equal to the plant withdrawal rate during 90 to 120 days of operation should be sufficient for seasonal variations. By using the summer consumption rate of 30 cfs/1200-MWe plant, a concentration ratio of 3, and a storage capacity equivalent to 100 days of full power operation, the capacity required per plant is $3.9 \times 10^8 \text{ ft}^3$, or about 9000 acre-ft. Although reservoir losses are neglected, the assumptions of the maximum water consumption rate and all units operating at full power should more than compensate for these losses.

There are many existing reservoirs having sufficiently large through-flows to be attractive for NEC sites. Many of these serve many purposes such as production of hydroelectric power; thus, there may be some concern about the loss of power output caused by the use of water by an NEC. This can be put in perspective by noting that an NEC will produce 40,000 kWe for each 1 cfs of water evaporated, as compared with about 7 kWe for the same amount of water dropping 100 ft through a hydroturbine.

7. ECOLOGY CONSIDERATIONS

The impact of the NEC water consumption and blowdown on the ecology of a lake or river basin must be considered in establishing the amount (or fraction) of water that can be consumed. The ecologist is most concerned about stream flow during periods of very low flow and during the spring runoff (freshet); for example, withdrawals and impoundment of the freshet may upset flood-triggered events such as breeding cycles. Regulation of rivers and the ultimate impact of this regulation on the river ecology is a complex problem. Results of Wollman and Bone⁴ indicate that the maintenance of oxygen levels of 4 mg/liter in rivers in most parts of the country will require an extensive reservoir system. Thus one is faced with the question of whether it is better to impound the freshet to augment low flow conditions to dilute wastes or to pass the freshet through the reservoir and have lower flows and probably lower quality during periods of low runoff. As will be noted in the next section, this question has little effect on either the river flow rates or the size of reservoirs required for an NEC.

Periods of very low flow will be the most difficult from an ecological viewpoint. The 90% duration flow (the flow equaled or exceeded 90% of the time) has been used as a low-flow criteria by fishery biologists in anadromous fish restoration because this flow is considered adequate to ensure a stream's usability for spawning. This flow criteria is probably conservative in that the 90% duration flow is about twice the 7-day, 10-year low flow for unregulated rivers.

Other factors that may limit the withdrawal rate from a river are (1) as the withdrawal rate is increased, the amount of life in the river that is drawn into and destroyed within the plant cooling system is increased, and (2) the consumption of water from lower river basins that feed estuaries must be evaluated from the standpoint of the effect on the estuary and the upstream movement of the salt front. The general importance of estuaries to the marine life cycle may severely restrict their use as either a water source or a point of discharge for blowdown.

8. RIVER FLOW REQUIREMENTS

The water resources required for an NEC will depend primarily on what fraction of the water can be consumed and whether storage (either existing or added) is used. The most important consideration is the availability and dependability of an adequate amount of water. As noted previously, the peak water consumption rate for each 1200-MWe unit is about 30 cfs, and this rate progresses arithmetically as the number of NEC units increases. The local water resources must be sufficient to reliably supply this quantity without serious impact on the area. Another significant factor concerns water quality (e.g., impurities and temperature) and its effect on requirements for water treatment and management of cooling tower blowdown.

There are some arid regions in western areas of the country with acute or impending water shortage problems where river flow criteria have no meaning because of the heavy water withdrawals already being practiced. These rivers, such as the Colorado, upper Snake, and Sacramento, must be evaluated on an individual basis, and, in general, any significant use of water from these rivers will require further basin development, purchase of water rights, or reallocation of these resources.

Although each site must eventually be judged on the basis of local considerations, the following general criteria will be used for screening purposes to identify areas that appear to have sufficient water to support an NEC. Restrictions affecting reactor siting or local institutional restraints on the use of water are not considered.

8.1 Criteria for River Flow Without Storage

The criteria used to evaluate the adequacy of a river to support an NEC, without storage, will consist of two factors. The first is that the maximum consumptive use will be no greater than 10% of either the 7-day, 10-year or the monthly, 20-year low flow. For many rivers, the flows for these two conditions are about the same. The second condition is that the withdrawal rate will be no greater than 15% of the 7-day,

10-year or monthly, 20-year low flow. These two conditions will be equally restrictive for a concentration ratio of 3. For concentration ratios less than 3 the withdrawal restriction will be limiting, and for ratios greater than 3 the consumptive use restriction will be limiting. These criteria will be based on projected flows for the rivers considering their current state of regulation and will be applied to both regulated and unregulated river systems.

These criteria can also be applied, with modifications to include plant factors, to the cumulative effects of several energy centers distributed along a major river system. (This is discussed in detail later.) Even for a single energy center, as the number of plants increases, the probability of having all plants in operation at the same time decreases. Thus the value used for water consumption and withdrawal rates becomes more conservative as the number of plants increases.

The ecological impact of these criteria can be evaluated by using approximations for unregulated rivers. The 90% duration flow, which corresponds to about 20% of the mean annual flow, has been used by fishery biologists in anadromous fish restoration programs as adequate to ensure a stream's usability by anadromous fish for spawning. For unregulated rivers, the 7-day, 10-year low flow is about half of the 90% duration flow, or 10% of the mean annual flow. A consumption rate of 10% of the 7-day, 10-year low flow implies that there will be a 5% reduction in the 90% duration flow. Because the accuracy of river flow measurements is about 5%, the impact of this consumption rate should be small. Furthermore, most river basins with sufficient flow to support an NEC will be at least partially developed with flow augmentation during months of minimum flow. It is probable that the 7-day, 10-year low flow on these regulated rivers, after 10% consumption by an NEC, will be greater than the 90% duration flow for the rivers in their natural state.

Restrictions on the withdrawal rate are to limit thermal discharges and the amount of aquatic life that is drawn into and destroyed within the NEC cooling system. With the withdrawal restricted to 15% of the 7-day, 10-year low flow, there would be a short period of from one to

several days during the life of the NEC in which the withdrawal rate would approach 20% if the center was operated at full capacity during this low flow period.

Also, for a consumption rate of 10% of river flow and a concentration ratio of 3, the thermal discharge due to blowdown flow will increase the mean river temperature by an amount between 5 and 6% of the temperature difference between the blowdown flow and the river (see Fig. 3). This would normally limit the river temperature rise to less than 3°F for the most adverse conditions of ambient air and river water temperatures. Even during those short time periods when the river flow rate is less than the 7-day, 10-year low flow, the river temperature rise, with the above restrictions, should be within the 5°F limit proposed by EPA.

The percent of the mean annual flow that may be consumed with these restrictions will vary widely, depending on the variability of seasonal runoff and the degree of stream regulation. By using approximations for unregulated eastern rivers, about 1% of the mean flow may be consumed. Two examples that show how widely this percentage may vary are the Arkansas and Tennessee Rivers. The Arkansas River at Little Rock has a mean annual flow of 39,800 cfs, but the projected monthly (October), 20-year low flow is expected to be only 2100 cfs.⁹ Using 10% of this 2100 cfs restricts the consumption to 210 cfs - 0.53% of the mean annual flow.

The Tennessee River is an example of a well-regulated river basin having relatively small variations in annual runoff. The mean annual flow near Paducah, Kentucky, is 63,100 cfs and the expected monthly (September), 20-year low flow is 23,600 cfs.⁹ Ten percent of this low flow is 2360 cfs, which is more than sufficient to supply a 40-reactor NEC. The allowable consumption rate assumed for this case would be 3.7% of the mean annual flow, over 7 times that of the Arkansas River.

In summary, for NECs without onsite storage, these criteria require a minimum 7-day, 10-year or monthly, 20-year low flow of 3000 cfs for 10 reactors and 12,000 cfs for 40 reactors. For rivers with poor water quality, the restrictions on the concentration ratio, and thus the withdrawal rate, may impose requirements for larger flows. However, for

screening purposes, the 7-day, 10-year or monthly, 20-year flow of 3000 cfs will be used to identify those areas having potential for supporting a 10-reactor complex.

8.2 Criteria for River Flow with Storage

Storage of water for use during periods of low river flow can add many potential NEC sites. In deriving a criterion for the river flow required for this case, neither the feasibility of building the reservoir nor the required capacity of the reservoir will be considered because these considerations are site-dependent and must be considered on a site-by-site basis.

Water may be stored by on-stream reservoirs or by pumping to special single-purpose off-stream reservoirs for an NEC. If the water use or resource requirement considerations are limited to water consumption and downstream effects, then requirements for the two systems are identical. Off-stream storage, which requires an additional pumping system with the water withdrawal rate limited by the river flow rate, is probably more expensive than on-stream storage. For site screening purposes, the water use criteria for both storage systems will be assumed the same, and the following discussion will be limited to on-stream storage.

The criteria for required river flows with storage will depend on whether the reservoir is intended for seasonal flow variations only or for both seasonal and annual variations. A rather cursory examination of the dependable yield data for rivers, such as those shown in Tables 4, 5, and 6 for the lower part of the White, Arkansas, and Mississippi Rivers,¹⁰ shows that storage for annual flow variations could be very difficult and expensive. Thus, for the purpose of this analysis, storage will be assumed to be for seasonal variations only, and the flow criteria will be based on low annual average flows.

The criterion assumed for determining the required flow with storage is that the consumption rate must not exceed 10% of the annual average low flow expected for any one year out of each 20 years (annual, 20-year low flow). The Arkansas and Tennessee Rivers are used as examples to show the extremes of the effect of this criterion on the percentage of

mean annual flow and monthly, 20-year low flows that will be consumed. Although the mean annual flow of the Arkansas River at Little Rock is 39,800 cfs, the annual, 20-year low flow is expected to be as low as 11,100 cfs.⁹ Ten percent of this low annual flow is, therefore, 1100 cfs. Although this 1100 cfs is only 2.78% of the mean annual flow, it is 52.9% of the expected monthly, 20-year low flow; that is, 52.9% of the normal reservoir through-flow could be consumed during this period. For such low flow periods, it would be necessary to draw on the reservoir to augment downstream flow.

The Tennessee River, at Paducah, Kentucky, has a mean annual flow of 63,000 cfs and an expected annual, 20-year low flow of 48,600 cfs.⁹ The criterion would permit the consumption of 4860 cfs, which is 7.7% of the mean annual flow and 20.6% of the projected monthly, 20-year low flow of 23,600 cfs. These examples again emphasize the desirability of locating NECs on controlled river systems having small variations in annual runoff.

Table 4. Dependable yield, White River at Clarendon, Arkansas, Station 7-0778, under regulated conditions

Consecutive years of lowest flow	Inclusive years	Average flow for inclusive years (cfs)	Percent of mean for period of record
1	1963	13,100	43.6
2	1963-64	15,400	51.3
3	1954-56	17,170	57.1
4	1953-56	19,480	64.8
5	1963-67	19,940	66.4
6	1962-67	20,980	69.8
7	1959-65	22,670	75.5
8	1960-67	23,090	76.8
9	1959-67	22,890	76.2
10	1959-68	24,230	80.6
47	1924-70	30,040	100.0

Table 5. Dependable yield, Arkansas River at Little Rock, Arkansas, Station 7-2635, under unregulated conditions

Consecutive years of lowest flow	Inclusive years	Average flow for inclusive years (cfs)	Percent of mean for period of record
1	1940	10,820	27.2
2	1963-64	14,990	37.6
3	1954-56	14,240	35.8
4	1953-56	16,920	42.5
5	1963-67	19,170	48.1
6	1962-67	23,120	58.1
7	1962-68	26,630	66.9
8	1963-70	29,160	73.2
9	1962-70	30,680	77.1
10	1931-40	30,560	76.8
43	1928-70	39,820	100.0

Table 6. Dependable yield at Station 72890.00, Mississippi River at Vicksburg, Mississippi

Consecutive years of lowest flow	Inclusive years	Average flow for inclusive years (1000 cfs)	Percent of 1929-1970 mean
1	1931-1931	272	49.2
2	1940-1941	330	59.7
3	1954-1956	394	71.4
4	1953-1956	409	74.0
5	1953-1957	441	79.9
6	1936-1941	473	85.7
7	1953-1959	473	85.7
8	1934-1941	478	86.5
9	1934-1942	491	88.9
10	1931-1940	495	89.7
42	1929-1970	552	100.0

The impact of this criterion on the ecology of the river and the water available for other uses is not severe. The ecologist is most concerned about maintaining adequate flows during the spring flood (freshet) or during periods of very low flow. In analyzing the flow requirements for the river ecology, it is assumed that the normal low river flow would be maintained by drawing on the reservoir during periods of low flow. The amount of water stored during the freshet (if any) need have little or no effect on either the amount of water that may be consumed by an NEC or the storage requirements for an NEC. There are several reasons for this. First, in most cases, the amount of water drawn from the reservoir during low river flows will be no greater than about 100 days of full power operation, which is less than 3% of the annual, 20-year low flow. Thus, even if no water is stored for one month during the freshet, there is still sufficient flow available to refill the reservoir before the next low flow season. Second, a low annual flow sometimes results from lack of a heavy runoff during the freshet, and there is little loss in letting this flow pass through the reservoir.

The effect of an NEC on the river ecology or, conversely, the effect of maintaining flow for river ecology on the flow available for an NEC can be shown by Fig. 15. This figure shows an assumed set of river flow conditions, plant water usage, and reservoir operation for a low-flow year. Although the river flow rates are assumed, the 90% duration flow (20% of the mean annual flow) and the low flow (10% of the mean annual flow) are typical of many U.S. rivers. Also, the annual low flow used in Fig. 15 (1/2 of the mean annual flow) is typical of the annual, 20-year low flow of many U.S. rivers.

The assumed conditions for Fig. 15 are a river mean annual flow of 6000 cfs, a 90% duration flow of 1200 cfs, a plant withdrawal rate of 450 cfs, and a plant consumption rate of 300 cfs (a 10-reactor energy center using 10% of the annual, 20-year low flow). The reservoir is assumed to be full at the end of March, and plant withdrawal requirements are to be met by using the reservoir during the freshet (April) or when withdrawal from the river would reduce the river flow below 1200 cfs. The reservoir is not used to augment low river flows when the flow drops

Fig. 15. River flow rates, plant water usage, and reservoir operation for a 10-reactor NEC.

below the 1200 cfs; however, if the plant blowdown is returned to the river during periods of low flow, this blowdown flow would add 150 cfs to the low river flow.

As shown in Fig. 15, the reservoir drawdown during the freshet is about 27,000 acre-ft and is rapidly refilled during early May. The maximum demand on the reservoir will be during extended low river flow conditions. For the conditions used in this example, the reservoir supplies all or part of the plant withdrawal requirements for about four months, results in a drawdown of about 90,000 acre-ft, and requires about six weeks to be refilled. The total water consumed by the plant is 10% of the total river flow during the year and about 20% of the flow not set aside for ecological considerations. Although the consumption rate used in this example was held constant near its maximum, in actual operation the water consumption and reservoir drawdown would be less. Also, the probability of all 10 reactors operating at full power for six months to one year is negligible. Furthermore, during part of the time that the reservoir is being used, the blowdown can probably be added to the river as part of the 90% duration flow of 1200 cfs.

In an average year the river flow would be about twice that shown in Fig. 15. The water consumed would be about 5% of the total river flow and about 7.5% of the flow not set aside for ecological considerations.

Other factors that must be considered from an overall water management viewpoint are the effects of reservoir operation on aquatic life and management of the blowdown. The percent of the total reservoir volume that is used should be limited to prevent excess loss of aquatic life. This will influence the reservoir capacity but not the required river flow rate. Another factor that must be evaluated is the effect of the blowdown on the river during periods of low flow. If this becomes a serious problem, then some off-stream storage may be needed to cool or store the blowdown until the reservoir's through-flow rate increases.

In summary, for streams having storage, a water availability criterion requiring an annual, 20-year low flow of 3000 cfs for 10 reactors and 12,000 cfs for 40 reactors appears reasonable for initially screening areas as potential NEC sites.

9. RIVER FLOW RATES

Maps of the United States (48 contiguous states) showing those rivers with sufficient flow to be of interest for various sizes of reactor complexes are shown in Figs. 16, 17, and 18. Figure 16 shows those rivers having mean annual flows greater than 3000 cfs. The river flow rates are also identified by ranges - 3000 to 6000, 6000 to 12,000, 12,000 to 24,000, and greater than 24,000 cfs. Although the mean annual flow is the most commonly reported value for river flow rates, it does not give any indication of the wide variability in the annual and seasonal runoff or their effects on flow rates. However, it does represent the maximum low flow potential of a completely developed river basin.

Figure 17 shows those rivers with an annual, 20-year low flow that is greater than 1500 cfs. The river flows are again identified by ranges, and for this case the ranges are 1500 to 3000, 3000 to 6000, 6000 to 12,000, and greater than 12,000 cfs. As discussed in Sect. 8.2, the annual, 20-year low flow is the flow criterion proposed for rivers with storage. By using this criterion for storage and a water consumption rate of 30 cfs/1200-MWe reactor (a required annual, 20-year flow rate of 300 cfs/1200-MWe reactor), the four flow ranges shown in Fig. 17 can support power generation complexes of 5 to 10, 10 to 20, 20 to 40, and greater than 40 reactors.

Figure 18 shows those rivers with monthly, 20-year low flows greater than 1500 cfs with the flow rates again identified by ranges of 1500 to 3000, 3000 to 6000, 6000 to 12,000, and greater than 12,000 cfs. The monthly, 20-year low flow is the criterion proposed for the case of no storage, and the flow ranges represent rates sufficient to support 5 to 10, 10 to 20, 20 to 40, and greater than 40 reactors without storage.

The purpose of these maps is to identify water resources and not to reflect restrictions that affect reactor siting or other needs or restrictions that affect water availability in the various regions. For example, both the Colorado and Sacramento Rivers are shown as being capable of supporting nuclear energy centers. However, diversion of water from the lower part of the rivers is such that the outflow from

ORNL DMG. 76-2745

Fig. 16. Mean annual river flow rates.

ORNL-DWG 76-4554

Fig. 17. Annual, 20-year low river flow rates.

ORNL-DWG 76-4555

Fig. 18. Monthly, 20-year low river flow rates.

these basins is insufficient for an energy center. Thus, any water utilization in this region would have to be at the expense of other uses. Another example is the Snake River. The upper Snake River in eastern Idaho and western Wyoming is shown in Figs. 16 and 17. However, west of Pocatello, Idaho, large irrigation uses and losses from the main channel to ground water flow reduces the flow below the level required for energy centers for about 100 miles. Also, as shown in Fig. 14, there are other large areas of the country that have been identified by the WRC as water critical areas. Thus, the location of energy centers in these regions may require establishment of priorities for the use of available water resources or the use of alternative cooling methods, such as dry cooling towers, or, where available, the use of seawater.

9.1 Data Sources, Limitations, and Interpretations

Several sources of data were used in determining the river flows. These included preliminary results of the WRC 1976 *Water Assessment*,² the comprehensive framework studies of various river basin commissions (e.g., the Columbia-North Pacific,¹¹ the Ohio,¹² or the lower Mississippi¹³), USGS data from water supply papers and computer tapes, and the 1968 WRC report *The Nation's Water Resources*. Where possible, the WRC 1976 *Water Assessment* data were used; however, these data are tabulated on an area basis, which in many cases, includes several rivers. An example of this type of data is shown in Table 7 for WRC region 01, aggregated subarea 01, which includes the St. John, Aroostook, Penobscot, Kennebec, and Androscoggin Rivers in Maine. The table shows the mean inflow and outflow on an annual basis as well as for each month and the probabilities (0.50, 0.80, 0.90, and 0.95) of a given flow being exceeded. Although the data for areas that combine the flow of several rivers do not provide data for individual rivers, it does give the probability of annual flows. The 0.95 probability values give an estimate of the low flow to be expected 1 year out of 20 years, and the difference between the outflow and inflow gives the probability of runoff from the area. Monthly flows are significantly influenced by lakes and reservoirs

Table 7. Surface water supply statistics for region 01, aggregate subarea 01^a

A. Summary of streamflow statistics											
Outflow from aggregate subarea 01						Inflow to aggregate subarea 01 ^b					
Period	Mean discharge	Discharge with indicated percent chance of being exceeded as a mean				Mean discharge	Discharge with indicated percent chance of being exceeded as a mean				
		50	80	90	95		50	80	90	95	
Annual	59,400	58,900	48,000	42,600	38,200	4,100	4,100	3,500	3,200	2,900	
October	34,300	28,100	18,000	14,300	11,900	3,000	2,300	1,200	890	680	
November	50,700	39,700	23,600	17,800	14,400	4,300	3,200	1,700	1,300	970	
December	55,900	45,000	27,000	20,500	16,600	2,600	2,100	1,200	900	690	
January	39,200	34,700	23,900	19,800	17,000	1,100	970	670	540	460	
February	37,600	32,800	22,000	17,900	15,200	840	730	480	380	310	
March	53,000	47,500	32,600	26,800	23,000	1,000	830	490	370	280	
April	152,000	140,000	100,000	84,400	74,000	10,900	9,400	6,000	4,700	3,800	
May	138,000	125,000	87,200	71,000	61,200	14,800	11,000	3,900	7,100	6,100	
June	52,100	47,300	33,100	27,600	23,900	3,700	2,700	1,600	1,200	900	
July	31,600	28,900	21,000	17,800	15,800	2,300	1,800	1,100	820	610	
August	29,100	25,400	17,800	14,900	13,200	2,700	1,500	610	370	270	
September	30,000	24,600	16,000	12,800	10,800	2,500	1,600	780	500	350	
B. Approximate monthly distribution of net evaporation (in inches)											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
-0.7	-2.4	-2.2	-2.0	-1.9	-1.8	-1.6	-1.5	-1.7	-0.9	-0.5	-0.8

^aAdditional statistics: Surface area of reservoirs = 630,000 acres; net annual surface import or export = 0 acre-ft; net annual reservoir evaporation rate = -18 in.

^bIf different from upstream aggregate subarea outflow.

Source: U.S. Water Resources Council, 1975 *Water Assessment*, to be published.

on the rivers; thus, the area data cannot be directly applied to obtain the probability of monthly flows.

The procedure used to estimate the individual river flows in this region was to obtain the mean annual flow from USGS data. The annual, 20-year low river flow was then calculated by multiplying the USGS mean annual flow by the ratio of the low annual flow expected 1 year in 20 years (the annual flow with an 0.95 chance of being exceeded) to the mean annual flow from the WRC regional data. This value was then checked with the USGS data. The estimated monthly, 20-year low flow was obtained by examination of monthly USGS data for the rivers. This estimate was made by visual examination of the data, and no detailed statistical analysis was made.

There are many regions in which the WRC 1975 Assessment data can be used directly. An example is shown in Table 8 for region 10, aggregate subarea 05, for the Missouri River between the Montana-North Dakota boundary and the Ft. Randall Dam (in southern South Dakota near the junction of the Missouri River and the Nebraska state line). The inflow to this area is the flow from aggregate subarea 04, the Yellowstone River, and aggregate subarea 01, the Missouri River at the Montana-North Dakota boundary. Thus, for this area, one has the mean annual flow, the annual, 20-year low flow, and the monthly, 20-year low flow at various locations along the river. The flow in the headwater areas, such as the upper end of the Yellowstone River in area 1004, is estimated from USGS and WRC data as for the case with the Maine Rivers.

The data of Table 8 (in combination with that of the upstream aggregate subarea 01 and 04) show some characteristics of western rivers, in which stream regulation has a significant effect on flow conditions. The mean annual inflow to the area is 22,800 cfs and the annual, 20-year low inflow is 13,100 cfs, as compared with outflows of 23,700 and 11,800 cfs respectively. Thus, while the mean annual flow increases slightly, the water use and evaporation exceeds the indigenous supply during dry years. The monthly (February), 20-year low flow of 2800 cfs shows the effect of river flow regulation and a problem in interpreting the data. The low February inflows to the area are 9100 and 3100 cfs,

Table 8. Surface water supply statistics for region 10, aggregate subarea 05^a

A. Summary of streamflow statistics											
Outflow from aggregate subarea 05											
Period	Mean discharge	Discharge with indicated percent chance of being exceeded as a mean									
		50	80	90	95						
Annual	23,700	23,700	17,800	15,000	11,800						
October	30,500	28,400	20,400	17,400	15,300						
November	26,500	22,500	14,000	10,900	8,700						
December	13,300	12,200	8,800	7,200	6,300						
January	11,300	10,300	7,200	5,900	5,100						
February	9,500	7,900	4,700	3,600	2,800						
March	14,200	12,400	8,100	6,400	5,300						
April	23,900	21,500	14,600	12,000	10,300						
May	27,300	26,500	21,600	19,400	17,700						
June	27,200	25,300	18,200	13,500	13,600						
July	31,800	30,800	24,500	21,600	19,700						
August	34,900	33,900	26,900	23,700	21,600						
September	33,700	32,700	25,900	22,900	20,900						
B. Approximate monthly distribution of evaporation as a percent of the net annual rate											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
12	4	1	0	1	1	4	6	9	20	23	19

^aAdditional statistics: Surface inflow to aggregate subarea = outflow from aggregate subareas 01 and 04 (region 10); surface area of reservoirs = 973,000 acres; net annual surface import or export = 0 acre-ft; net annual reservoir evaporation rate = 28 in.

Source: U.S. Water Resources Council, 1975 *Water Assessment*, to be published.

or a minimum total of 12,200 cfs (this value is a minimum and would be this low only if the inflow from the two upstream areas were a minimum in the same year). Thus, rather large quantities of water are stored during this period. An examination of USGS data for intermediate points in this area indicates that water is stored in most of the main stem reservoirs in this region (primarily Garrison, Oahe, and Ft. Randall, having reservoir capacities of 24.4×10^6 , 23.6×10^6 , and 5.7×10^6 acre-ft respectively) during the winter. Reference 13 states that releases of water during the winter (from late November to late March when ice conditions prevent use of the river for navigation) are made to maintain satisfactory downstream water quality. The water impounded during this period is released during the 8-month navigation season to maintain adequate channel depth. It is also interesting to note that the total storage capacity of the main stem reservoirs is over 75×10^6 acre-ft, or greater than three times the mean annual flow from the lowermost dam. Thus, the extensive development of the Missouri River Basin has a pronounced effect on seasonal flow and has sufficient capacity to influence annual flows.

The low February flow also brings out a problem in relating the water flow rates of Figs. 17 and 18 to the generating capacity that the river can support. The criteria for flow without storage would limit the number of reactors to nine. However, the lowest flow occurs only in February when the water consumption rate is considerably less than the 30 cfs/1200-MWe plant typical of hot weather conditions, and a total of 11 or 12 reactors could be supplied without consumption exceeding 10% of the flow. However, if the current winter release rates are just sufficient to provide dilution flow for downstream wastes, then large consumptive uses of water could require larger winter releases and thus reduce the water available for augmenting flows during the navigation season.

In some areas, primarily the Columbia-North Pacific, the Ohio River, and the lower Mississippi River basins, the comprehensive framework studies¹⁰⁻¹³ included detailed statistical data of river flows. The results presented in these studies, along with the WRC data, were used for estimating flows.

There is a basic difference in the manner in which the low monthly flows are presented in the various data sources. The comprehensive framework studies¹⁰⁻¹³ give 30-day low flows, whereas the procedure used to extract data from the USGS computer tapes gave monthly averages from which low flows were obtained. The 30-day value implies that the lowest flow over 30 consecutive days was used. This would be lower, in most cases, than the monthly averaged low flow, but the difference probably would be small. The WRC data reports low monthly flows by each specific month and can be different from the 30-day or monthly flows, which can be for any 30 days or any month. In most cases rivers have flow characteristics such that the low flow occurs during one season (usually late summer or fall), and the differences in the above methods of analysis are probably within about 10%.

9.2 Power Capacity of Major River Basins

The data presented in Figs. 17 and 18 show those rivers having sufficient flow to support various sizes of reactor complexes, but in most cases do not give the limits to the total number of reactors or power plants that the river basin can accommodate. As noted previously, the criteria used for the maps were based on near-peak water consumption during the summer and on full-power operation of all units; that is, no consideration was given to plant factor or to seasonal variation in water consumption per unit of output.

Although these assumptions are reasonably valid for streams with low flows of less than 8000 to 10,000 cfs, they are too restrictive to be applied to a large river basin that can support a large number of power plants. For example, WASH-1139¹⁴ estimates a plant load factor of 65 to 70% for nuclear plants. This implies that the total installed capacity on a large river system could be increased by as much as 50% or, conversely, the plant factor could reduce the average water consumption to about 20 cfs per 1200 MWe of installed capacity.

In evaluating the power plant capacity that can be installed on a river basin, the mix of nuclear and fossil-fired units should be considered. Case A of WASH-1139¹⁴ estimated that, for the year 2000, about

54% of the total installed generating capacity will be nuclear. For this analysis, the remaining 46% will be assumed to be supplied by fossil-fired units. Modern fossil-fired plants have a base-load efficiency of about 40% and reject about 50% of the heat input to the cooling water. With wet cooling towers, this results in a summer water consumption rate of about 18 cfs per 1200 MWe of power output. However, most power projections assume that the fossil-fired plants will be load-following, which will reduce their load factor and efficiency. The exact efficiency will depend on the degree of cycling and the fraction of full-load operation. The combined effects of the lower part-load efficiency and the load factor for these plants will result in a water consumption rate of about 15 cfs per 1200 MWe of installed capacity. Thus, the summer water consumption rate for the expected mix of nuclear and fossil-fired plants will be about 17 to 18 cfs per 1200 MWe of installed capacity.

Finally, the water consumption rate during cold weather conditions will be reduced and will depend on the site location and the mode of operation of the cooling system during this time. Taking all factors together, 16 cfs per 1200 MWe of installed capacity becomes a reasonable average value for water consumption on the larger river basins; this value is used in the following analysis.

Table 9 gives estimates of the mean annual flow, the annual, 20-year low flow, and the monthly, 20-year low flow at the outlet of the major river basins. Also shown is the number of power plants of all types that could be accommodated by these flows if using a required river flow rate of 160 cfs (a consumption rate of 10% of the low flow condition) per 1200 MWe of installed capacity. The number of power plants shown for both cases, with and without storage, provides some insight to availability of water resources; a far more detailed analysis of load factors and seasonal timing of peak loads would be required to arrive at firm estimates. For the smaller rivers shown in the table, especially those for which less than 20 plants are allowable, the diversity due to plant load factors may not be fully realized, and the number of plants may not be quite as large as shown.

Table 9. Estimated outflow² of major U.S. river basins and number of 1200-MWe power plants that can be located upstream

River basin	Flow (cfs)			Number of power plants	
	Mean annual	Annual, 20-year	Monthly, 20-year	With storage	Without storage
Connecticut	18,600	11,600	2,800	72	17
Hudson	24,200	15,600	4,200	97	26
Delaware	24,300	14,200	3,900	88	24
Susquehanna ^b	37,900	26,300	3,400	164	21
Apalachicola ^b	24,200	15,200	8,000	95	50
Mobile	64,000	39,800	9,000	248	56
Alabama	32,400	21,100	6,700	131	41
Tombigbee	32,200	18,700	1,600	116	10
Mississippi-Atchafalaya	615,000	390,000	150,000	2437	937
Illinois ^c	20,600	10,500	4,800	65	30
Missouri	70,800	28,300	13,400	176	83
Ohio	276,000	162,000	41,700	1012	260
Allegheny-Monongahela	30,500	22,000	5,000	137	31
Wabash	30,500	12,100	2,100	75	13
Cumberland	33,400	18,000	4,000	112	25
Tennessee	63,100	48,600	23,600	303	147
White ^d	30,000	15,000	8,000	94	50
Arkansas	39,800	11,100	2,100	69	13
Red	30,500	10,100	1,600	63	10
Columbia ^e	240,000	170,000	110,000	1062	688
Snake	56,200	38,200	17,400	238	108
Willamette ^c	38,500	24,200	5,400	150	33
St. Lawrence ^b	240,000	190,000	160,000	1187	1000

^a Flows are from WRC data unless noted otherwise; these flows are from the WRC water regions and in some cases are not the flow from the mouth of the river.

^b From USGS data.

^c U.S. Army Engineer Division, Ohio River, *Ohio River Basin Comprehensive Study*, Appendix C, Cincinnati, Ohio, August 1966.

^d Lower Mississippi Region Comprehensive Study Coordinating Committee, *Lower Mississippi Region Comprehensive Study*, Appendix C, 1974.

^e Pacific Northwest River Basins Commission, *Columbia-North Pacific Region Comprehensive Framework Study*, Appendix V, vols. 1 and 2, Vancouver, Washington, April 1970.

Table 9 emphasizes the large difference in the annual, 20-year low flow and the monthly, 20-year low flow and thus the number of power plants that can be supported with and without storage. This difference reflects both the seasonal variation in runoff and the degree of development or regulation of the river basin. The "with storage" case does not necessarily require that the power plants be located on a reservoir. It is possible to obtain the same results by building upstream reservoirs to adjust for seasonal variations in flow. However, to reach the total number of plants shown under the "with storage" heading would require that the plants be built on reservoirs or that sufficient storage be provided to eliminate seasonal flow variations. The number of power plants shown under the "without storage" column represents the total number that might be accommodated by the river system with the current degree of regulation; again, for power utilization a limit of 10% of the monthly, 20-year low flow is used.

The total mean annual runoff from the United States (48 states, excluding runoff from Canada) is 1,860,000 cfs.² The annual, 20-year low flow (ref. 2) for the various WRC regions can be calculated at 1,018,000 cfs, or about 55% of the mean. This value is probably lower than the actual annual, 20-year runoff because the dry years are not the same for all regions of the country. Part of this runoff is in small coastal rivers that are too small for power plants, and some is in areas that are unsuitable for other reasons. However, the mean annual flow from the three largest rivers (including runoff from Canada), the Mississippi-Atchafalaya, the Columbia, and the St. Lawrence, is 1,095,000 cfs. The annual, 20-year and the monthly, 20-year low flows for these rivers are 750,000 and 435,000 cfs respectively.

The total installed power capacity for the United States in the year 2000 is estimated to be about 1,575,000 MWe (from case A of WASH-1139),¹⁴ or the equivalent of 1312 plants, each producing 1200 MWe. By using the same assumptions for water as above, total consumption would be about 21,000 cfs, which requires a total river flow of 210,000 cfs. In practice, since part of this capacity will be provided by hydroelectric power and part will be cooled by seawater, the freshwater requirements for power plant cooling need not place a serious burden on the

total amount of water available. Furthermore, some fraction of the water evaporated will be returned to the continent as additional precipitation downwind of the NECs, and part of this will show up as increased runoff to the various river basins. In summary, any restrictions on power plants due to water availability result from the distribution rather than the total availability of resources.

10. REGIONAL WATER RESOURCES AND REQUIREMENTS

There are several ways to analyze water resources for power requirements. One method is rather broad and compares the overall availability of water (as determined by runoff) to the demand. A second, more site-specific approach is concerned with the distribution of water, the concentration of runoff in rivers and streams, and the ecological impact of large energy centers on the flows. Either of these approaches must address the question of the reliability of runoff and streamflows. The following analysis of regional water resources discusses both aspects with primary emphasis on streamflows and the identification of rivers with sufficient flow to support various sizes of energy centers.

Some perspective of possible problems in providing for future power growth can be obtained by considering future power density requirements (megawatts per square mile). The projected power capacity requirements for the 48 contiguous states for the years 2000 and 2020 are 1,575,000 and 3,000,000 MWe respectively. With an area of 3,000,000 sq miles, the power densities are 0.53 MWe/sq mile and 1.0 MWe/sq mile. A power density of 1.0 MWe/sq mile will consume water, at full-power output, at the rate of 0.025 cfs/sq mile, or, expressed in terms of runoff, about 0.34 in. per year. Including overall plant factors and allowing for lower water consumption during cold weather reduces this value to about 0.18 in. per year for each 1 MWe/sq mile of installed capacity. The average runoff for the United States is about 8.4 in. per year.

Another way of getting an overall view of future power requirements and the relative merits of energy centers is to determine the area that can be served by centers of various sizes. For example, with a power density requirement of 1 MWe/sq mile, a 1200-MWe plant will serve 1200 sq miles and, if the plants are assumed to be located in a rectangular pattern across the country, would require one 1200-MWe unit every 34.6 miles. Comparable distances for energy centers of five, ten, and forty 1200-MWe units would be 77, 110, and 219 miles respectively. There are wide variations in power density requirements throughout the country, and some regions can use the output of large energy centers in relatively small areas.

In examining the regional water resources and requirements for power, a total of eleven regions were used. These regions follow the general outline used in the *National Atlas* except that states are not split between regions. A list of the regions and the states included in each are shown in Table 10. Table 10 also gives a compilation of water data for each region and projections of installed power capacity for the year 2020. The water data are given in terms of inches per year, cfs, and cfs per capita, and, with the exception of the per capita data, are for both the average and the annual, 20-year low flow (or runoff). The per capita data are for the annual, 20-year low flow and 1970 census data. The cooling water consumption rates for the installed capacity for the year 2020 are based on an annual consumption rate of 16 cfs per 1200 MWe of installed capacity. The distance between various sizes of energy centers is based on a simple rectangular pattern of sites and capacity projections for the year 2020.

In the following discussion of regional water resources, primary emphasis is placed on the availability of resources in comparison with requirements for power generation. The political, economic, and environmental problems associated with the development of water resources and the use of land for power plants and transmission corridors, although very important in some areas of the country, are not addressed here.

10.1 Northeast Region

The northeast region has the highest, and least variable, runoff (inches per year) of any region in the country. The total runoff averages 186,000 cfs, and the annual, 20-year low runoff is 132,000 cfs. If all cooling for power generation were provided by wet cooling towers using fresh water, the consumption by 2020 would be about 3900 cfs, or 3.0% of the annual, 20-year low runoff. The region has access to two of the Great Lakes, the St. Lawrence River, the Atlantic Ocean, and over twenty rivers having an annual, 20-year low flow in excess of 1500 cfs. (Of these rivers, ten have flows greater than 3000 cfs.)

Table 11 lists the rivers in or bordering this region which have mean annual flows greater than 3000 cfs, annual, 20-year low flows

Table 10. Projected electrical capacity requirements for year 2020 and water data by region

Region	States	Indigenous runoff				Runoff per capita ^a (10 ⁻³ cfs)	Electrical capacity		Cooling water consumption ^c (1000 cfs)	Distance between sites ^d			
		In in./year		In 1000 cfs			Total (1000 MW)	Density (MW/sq mile)		Single units	5 units	10 units	40 units
		Av	Low ^b	Av	Low ^b								
Northeast	Maine, New Hampshire, Vermont, New York, Massachusetts, Connecticut, Rhode Island	21.8	15.4	186	132	4.4	293	2.5	3.9	22	49	69	139
Middle Atlantic	New Jersey, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, Ohio, District of Columbia	16.0	10.0	202	127	3.1	534	3.2	7.1	19	43	61	122
South Atlantic	North Carolina, South Carolina, Georgia	14.2	8.4	149	88	7.2	244	1.7	3.3	26	59	84	168
Florida	Florida	11.0	4.4	47	19	2.8	214	3.7	2.9	18	41	57	115
South central	Alabama, Mississippi, Louisiana, Arkansas, Tennessee	18.1	9.6	324	172	11.4	251	1.0	3.3	34	76	108	216
Midwest	Missouri, Illinois, Kentucky, Indiana, Iowa	10.5	4.2	200	80	3.0	368	1.4	4.9	29	65	92	184
Northern Great Lakes	Michigan, Wisconsin, Minnesota	7.7	4.5	113	66	3.3	209	1.1	2.8	34	75	107	213
Central plains	Nebraska, Kansas, Colorado	2.4	0.9	46	17	2.9	64	0.2	0.9	70	157	222	445
Southwest	Oklahoma, Texas, New Mexico, Arizona	2.5	0.7	107	30	1.8	337	0.6	4.5	45	101	143	286
Northwest	North Dakota, South Dakota, Montana, Wyoming, Idaho, Washington, Oregon	8.0	5.2	374	242	28.4	113	0.2	1.5	82	183	259	518
California-Great Basin	Utah, Nevada, California	4.3	1.8	112	47	2.2	372	1.1	5.0	34	76	107	214

^aAnnual, 20-year low flow (or runoff).^bBased on 1970 Census and annual, 20-year low runoff.^cWater consumption is based on 16 cfs/1200-MW unit.^dPlants assumed to be in a rectangular array throughout the region with one, five, ten, or forty 1200-MW units per site.

Table 11. Water resources for the northeast region^a

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Atlantic Ocean tributaries (via St. Lawrence)</i>												
St. Lawrence				X				X				X
Niagara				X				X				X
Genesee					X							
Oneida	X	X			X	X						
Seneca	X				X							
Black	X				X							
Lake Champlain- Richelieu	X	X			X	X	X		X			
<i>Atlantic Ocean tributaries</i>												
St. John	X	X			X	X	X					
Aroostook					X							
Penobscot	X	X	X		X	X	X		X	X		
Kennebec	X	X			X	X			X			
Androscoggin	X	X			X	X			X			
Saco	X				X							
Merrimac	X	X			X	X						
Connecticut	X	X	X		X	X	X		X			
Housatonic	X				X							
Hudson	X	X	X		X	X	X	X	X	X		
Mohawk	X				X	X						
Delaware	X				X	X						
Susquehanna	X	X			X	X						
Chenango					X							
Chemung					X							
<i>Gulf of Mexico tributaries (via Ohio-Mississippi)</i>												
Allegheny					X							

^aSee Table 10 for states included in the Northeast region.

greater than 1500 cfs, and monthly, 20-year low flows greater than 1500 cfs. The range of flow rates (see Figs. 16, 17, and 18) are also indicated for each river. The rivers having annual, 20-year low flows greater than 1500 cfs in this region are also shown in Fig. 19.

Table 11 can be used as an aid to identify the rivers shown on the U.S. and regional maps. The rivers are listed under the heading of the ocean (or gulf) to which they eventually flow. For the northeast region, the Atlantic Ocean tributaries are listed from north to south. Inland rivers are listed starting with the river farthest upstream. The tributaries to the Great Lakes are listed as if the Great Lakes were a river system, with the river farthest upstream from the St. Lawrence River listed first. For those regions in which two rivers combine to form a third, the eastern or northern tributary is listed first.

From an overall regional viewpoint, the northeast has sufficient water resources. The problems associated with the region are described in a WRC report,⁶ from which the following quote is taken:

The most serious water supply problem associated with energy development exists in the coastal portion of the New England and northern portions of the Mid-Atlantic Regions. Whether the development is power plants, oil terminals, refineries, tank farms, or other energy developments, the primary problem is the incompatibility of development with the desire for return to or maintenance of a natural environment on the part of a large vocal segment of the population. Reservoirs have been proposed and authorized to solve most of the problems of seasonal variations in stream flow, only to be held up by these naturalists. Siting of oil terminals in New England has been shunted from site to site by objections of local people to construction at particular sites. These are just examples of the same type of problem which exists with all types of water resources development whether or not related to energy.

The same WRC report, in reference to the Great Lakes, notes that water quality of the lakes is of primary importance with respect to water availability and that quality, rather than quantity, may serve as a limiting factor in water resources utilization.

This region, with its large load centers, is a prime candidate for large energy centers. From the viewpoint of water resources, there

Fig. 19. Rivers having an annual, 20-year low flow greater than 1500 cfs — northeast region.

appears to be little, if any, difference between small dispersed sites and large centers. In view of the problems currently being encountered in this region, a smaller number of very large installations may be preferable.

10.2 Middle Atlantic Region

The middle Atlantic region has the largest projected electrical capacity (534,000 MWe) of any region. The water resources and problems in this region are similar to those of the northeast region, and the WRC quotation given in the previous section refers also to this region. The overall total water resources are about the same as for the northeast, but smaller on a per capita basis. The region has access to Lake Erie, the Atlantic Ocean, and over twenty rivers having annual, 20-year low flows in excess of 1500 cfs. (Of these rivers, ten have flows in excess of 3000 cfs.) This region also has the largest estuaries in the country. However, the general importance of estuaries to the marine life cycle may severely restrict their use as a source for cooling water.

Table 12 lists the larger rivers in or bordering this region. The criteria for listing, the ranges shown, and the format for identifying rivers are the same as for Table 11. The map of Fig. 20 shows those rivers having an annual, 20-year low flow greater than 1500 cfs.

The distribution of load centers and water resources are fairly well matched in this region. In general, the larger load centers are on, or within a short distance of, water supplies sufficient to serve their needs. For example, there are five load centers that require the capacity equivalent to 30 or more 1200-MWe units. These are Newark-Jersey City, Philadelphia, Washington, Cleveland, and Pittsburgh. Newark-Jersey City is on the lower Hudson River and the Atlantic Ocean; Philadelphia is on the Delaware River and within about 50 miles of the Atlantic Ocean; Washington is on the Potomac and within about 75 miles of the lower part of the Susquehanna River; Cleveland is on Lake Erie; and Pittsburgh is on the Ohio River. Thus, this area is especially well suited for large energy centers.

Table 12. Water resources for the middle Atlantic region^d

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	1000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Atlantic Ocean tributaries (via St. Lawrence)</i>												
Maumee	X											
<i>Atlantic Ocean tributaries</i>												
Hudson			X					X			X	
Delaware	X	X	X		X	X	X		X		X	
Susquehanna	X	X	X	X	X	X	X	X	X		X	
Chesung					X							
West Branch Susquehanna	X	X			X	X	X					
Junata	X				X							
Foromac	X	X			X	X						
James	X	X			X	X						
Roanoke	X	X			X	X			X			
Pan					X							
<i>Gulf of Mexico tributaries (via Ohio-Mississippi)</i>												
Ohio				X				X		X		X
Allegheny	X	X	X		X	X	X	X	X			
Monongahela	X	X	X		X	X	X		X			
Tygart Valley					X							
Cheat					X							
Youghiogheny					X							
Beaver	X				X							
Muskingum	X	X			X	X						
Kanawha			X				X		X			
New	X	X			X	X						
Gauley					X							
Big Sandy	X				X							
Scioto	X				X							
Great Miami	X											

^dSee Table 10 for states included in the middle Atlantic region.

Fig. 20. Rivers having an annual, 20-year low flow greater than 1500 cfs - middle Atlantic region.

10.3 South Atlantic Region

Although the south Atlantic region does not contain any large river basins, it does contain many smaller rivers capable of supporting small energy centers (5 to 20 units) and has access to the Atlantic Ocean. The region has one of the higher per capita runoffs, and water resources should be sufficient to meet future requirements.

A list of the larger rivers in this region is given in Table 13 and the map of Fig. 21 shows those rivers having an annual, 20-year low flow greater than 1500 cfs.

This region does have the problem that the large sources of cooling water are in the coastal areas, whereas the major load centers are inland. The largest load center is Atlanta, and the nearest source of cooling water large enough to meet the Atlanta requirement (60,000 MWe) in year 2020 is the Tennessee River (about 100 miles away) in the south central region. Although the loads and water distribution are poorly matched, the distances involved are not large; therefore, a combination of coastal energy centers and smaller, inland, dispersed plants should serve the area without excessive electrical transmission distances.

10.4 Florida Region

Florida has the largest projected density of installed electrical capacity (3.7 MWe/sq miles) of any region. Furthermore, about 175 of the 214 MWe projected for the region are concentrated in the southern half of the state - an area short of fresh water and without any rivers capable of supporting even small energy centers. Fortunately, no part of this region is more than 75 miles from the Atlantic Ocean or the Gulf of Mexico. The load distribution in the southern part of the region is ideal for large coastal energy centers. The northwest part of the region has rather low power requirements, and both fresh and sea water are available for cooling.

A list of the larger rivers in this region is given in Table 14, and the map of Fig. 22 shows those rivers having an annual, 20-year low flow greater than 1500 cfs. The format for Table 14 is the same as for

Table 13. Water resources for the south Atlantic region^d

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	1000- 6000	6000- 12,000	12,000- 24,000	>24,000	1000- 3000	3000- 6000	6000- 12,000	>12,000	1000- 3000	3000- 6000	6000- 12,000	>12,000
<i>Atlantic Ocean tributaries</i>												
Roanoke		X				X			X			
Neuse	X				X							
Cape Fear	X				X							
Yadkin-Pee Dee	X	X	X		X	X	X		X			
Little Pee Dee	X											
Santee ^b			X				X				X	
Catawba-Wateree	X	X			X	X						
Congaree		X				X			X			
Broad	X	X			X	X						
Cooper ^b			X				X				X	
Savannah	X	X			X	X	X		X	X		
Altamaha		X	X			X	X		X	A		
Oconee	X				X							
Ocmulgee	X				X	X						
<i>Gulf of Mexico tributaries (via Apalachicola)</i>												
Flint	X	X			X	X			X			
Chattahoochee	X	X			X	X	X		X	X		
<i>Gulf of Mexico tributaries (via Mobile)</i>												
Cusa		X				X						
Oostaula	X				X							
Etowah					X							
<i>Gulf of Mexico tributaries (via Tennessee-Ohio-Mississippi)</i>												
French Broad					X							
Little Tennessee	X				X							

^dSee Table 10 for states included in the south Atlantic region.^bMost of the flow is diverted from the lower Santee River to the Cooper River.

Fig. 21. Rivers having an annual, 20-year low flow greater than 1500 cfs - south Atlantic region.

Table 14. Water resources for Florida^a

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Atlantic Ocean tributaries</i>												
St. Johns	X	X			X							
<i>Gulf of Mexico tributaries</i>												
Suwannee	X	X			X	X			X	X		
Apalachicola			X	X				X			X	
Choctawhatchee	X	X			X	X			X			
Escambia		X				X						
Conecuh	X				X							

^aThis region consists of only the state of Florida.

Fig. 22. Rivers having an annual, 20-year low flow greater than 1500 cfs -- Florida region.

the previous sections. The Gulf of Mexico tributaries are listed from east to west.

10.5 South Central Region

The south central region has an abundant runoff of water plus an enormous inflow from upstream regions. Water resources are well distributed throughout the region, and decisions concerning energy centers vs dispersed sites will not depend on availability of cooling water. In general, the largest load centers are on rivers having sufficient cooling water to meet their power requirements.

A list of the larger rivers in this region is given in Table 15, and the map of Fig. 23 shows those rivers having an annual, 20-year low flow greater than 1500 cfs.

10.6 Midwest Region

The indigenous runoff from the midwest region is not large on a per capita basis or in terms of cooling water requirements, which are projected to be about 6% of the indigenous runoff. However, the large inflows to the region from the upper parts of the Missouri, Mississippi, and Ohio Rivers and access to and withdrawals from Lake Michigan by the city of Chicago should be adequate for future requirements. The water resources available to this region are concentrated in large rivers and are well distributed throughout the region. The larger load centers in this region are also located on or near the water resources. This region appears to be especially well suited for large energy centers.

A list of larger rivers in this region is given in Table 16, and the map of Fig. 24 shows those rivers with an annual, 20-year low flow greater than 1500 cfs.

10.7 Northern Great Lakes Region

Most of the cooling water for power generation in the northern Great Lakes region must be supplied by the lakes. Energy-related problems in part of this area may be associated with water quality and

Table 15. Water resources for the south central region^d

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Gulf of Mexico tributaries</i>												
Conecuh (via Escambia)	X				X							
Mobile				X				X			X	
Alabama			X	X				X		X	X	
Coosa		X	X			X	X		X			
Tallapoosa	X				X	X			X			
Tombigbee	X	X	X	X	X	X		X	X			
Black Warrior		X				X						
Mulberry Fork	X				X							
Pascagoula		X				X						
Chickasawhay	X				X							
Leaf	X				X							
Pearl	X	X			X	X						
Mississippi-Atchafalaya				X				X				X
Cumberland (via Ohio)		X	X	X		X	X	X		X		
Caney Fork	X				X							
Tennessee (via Ohio)			X	X			X	X		X	X	X
Holston	X				X							
French Broad	X	X			X	X			X			
Little Tennessee	X				X	X			X			
Clinch	X				X	X			X			
Hiwassee	X				X	X			X			
Eik	X				X							
Duck	X				X							
Natchie					X							

Table 15 (continued)

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
St. Francis	X	X			X	X						
White	X	X	X	X	X	X	X	X	X	X	X	
Black	X	X			X	X			X			
Current					X							
Arkansas				X			X		X			
Yazoo		X				X	X		X			
Tallahatchie-Little Tallahatchie	X	X			X							
Big Black	X				X							
Red		X	X	X		X	X	X	X	X		
Little	X				X							
Quachita	X	X	X		X	X	X					
Sabine	X	X			X							

^aSee Table 10 for states included in the south central region.

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Fig. 23. Rivers having an annual, 20-year low flow greater than 1500 cfs -- south central region.

Table 16. Water resources for the midwest region¹

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
Gulf of Mexico tributaries												
Mississippi				X				X			X	X
Rock	X				X							
Iowa		X			X							
Cedar	X											
Des Moines	X											
Illinois			X				X			X		
Kankakee	X				X							
Des Plaines		X				X			X			
Sagamon	X											
Missouri				X				X			X	X
Grand	X											
Ozage	X	X			X							
Kankaskia	X											
Ohio				X				X			X	X
Big Sandy	X				X							
Licking	X				X							
Great Miami	X											
Kentucky	X	X			X	X						
Green	X	X			X	X						
Wabash	X	X	X	X	X	X	X		X			
White	X	X			X	X						
East Fork White	X				X							
Cumberland	X	X		X	X	X		X		X		
Tennessee				X				X				X
White	X				X							
Current (via Black)					X							
Atlantic Ocean tributary (via St. Lawrence)												
St. Joseph	X				X							

¹See Table 10 for states included in the midwest region.

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Fig. 24. Rivers having an annual, 20-year low flow greater than 1500 cfs - midwest region.

land use. The WRC discussion of developing problems in the Great Lakes Basin is quoted below:⁶

Energy-related water problems in the Great Lakes Region are associated with providing sufficient land for power plant sites along the Great Lakes and the thermal and perhaps consumptive use effects of additional cooling needs.

The land requirements for power facilities must compete with those of other industries, housing, public facilities, etc. Power facilities must also overcome opposition from the public and communities which have become increasingly concerned with the appearance of the surroundings and with the environmental quality of the air and landscape.

Water quality is of primary importance with respect to water availability and may serve as a limiting factor in water resource utilization rather than a shortage of water per se. The increasing use of evaporative cooling measures should ultimately minimize any thermally induced impact on water quality.

Water supply problems may arise in certain areas within the Basin; however, with sound water resource management, these should not be severe. It must be emphasized that the criteria for land use, in conjunction with water use, cannot be overlooked, and this may be the single most important factor in facilitating or restricting future water resource development in the Great Lakes Basin.

The power density characteristics of the region are diverse, with only a few large load centers. The northern part of the region does not appear to be well suited for energy centers unless centers located in this area send power into the southern and eastern parts of the region. The western part of the region has neither the demand nor the resources for an energy center.

A list of the larger rivers in this region is given in Table 17, and the map of Fig. 25 shows those rivers having an annual, 20-year low flow greater than 1500 cfs.

10.8 Central Plains Region

The only water resources of sufficient size to support even a 5-unit complex in the central plains region are along the Missouri River

Table 17. Water resources for the northern Great Lakes region^a

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 4000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6,000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Atlantic Ocean tributaries (via St. Lawrence)</i>												
St. Louis					X							
St. Mary's				X				X				X
St. Joseph	X				X							
Grand	X				X							
Fox	X				X							
Mnominiee	X				X							
St. Clair				X				X				X
Detroit				X				X				X
<i>Gulf of Mexico tributaries</i>												
Mississippi	X	X	X	X	X	X	X	X	X	X	X	X
Minnesota	X											
St. Croix	X				X				X			
Chippewa	X	X			X	X			X			
Wisconsin	X	X			X	X			X			
<i>Hudson Bay tributaries</i>												
Red	X											
Rainy			X				X			X		

^aSee Table 10 for states included in the northern Great Lakes region.

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Fig. 25. Rivers having an annual, 20-year low flow greater than 1500 cfs -- northern Great Lakes region.

at the eastern boundary of the region. Although the Colorado River is shown in Table 18 and on the map of the region (Fig. 26), diversion of water from the lower Colorado is so extensive that the outflow is not sufficient for an energy center. Thus, any utilization of this water would be at the expense of other uses.

This region has neither the resources nor load characteristics for large energy centers to be attractive. The only large load center is the Denver area with a projected capacity of about 30,000 MWe. The nearest river having sufficient flow to serve this size of load is the Missouri River, about 400 miles away.

The total cooling water consumption required for the projected power requirements is about 2% of the mean annual runoff from the region and about 5 to 6% of the annual, 20-year low runoff. Thus, development of existing water resources should enable the region to meet the projected cooling water requirements with dispersed plants.

10.9 Southwest Region

On an overall basis, the southwest region has the lowest per capita runoff and the highest cooling water requirement, in relation to runoff, of any region. The problem is tempered somewhat because most of the required power capacity and the largest load centers are in the eastern part of the region, which contains most of the fresh water resources and which is also within a reasonable distance from the Gulf of Mexico. Large energy centers along the Gulf and smaller centers on the Red and Arkansas Rivers in the extreme eastern part of the region (see Fig. 27 and Table 19) would place about 75 to 85% of the required capacity within about 250 miles of the demand.

Arizona, New Mexico, and the western part of Texas already have water supply problems, which will probably get worse (see Fig. 14). This area is faced with the alternatives of importing power over long transmission distances, using dry cooling systems, or obtaining rights to water currently being used for agriculture.

Table 18. Water resources for the central plains region^a

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Gulf of Mexico tributaries</i>												
Missouri			X	X			X	X	X	X	X	
Platte	X				X	X						
Kansas	X	X			X							
<i>Pacific Ocean tributaries</i>												
Colorado	X	X			X	X			X			
Green	X				X							

^aSee Table 10 for states included in the central plains region.

Fig. 26. Rivers having an annual, 20-year low flow greater than 1500 cfs -- central plains regions.

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Fig. 27. Rivers having an annual, 20-year low flow region greater than 1500 cfs -- southwest region.

Table 19. Water resources for the southwest region^d

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Gulf of Mexico tributaries (via Mississippi)</i>												
Arkansas	X	X	X	X	X	X	X		X			
Neesho	X	X			X							
Verdigris	X											
Canadian	X											
Red	X	X			X	X						
Little					X							
<i>Gulf of Mexico tributaries</i>												
Sabine	X	X			X							
Neches	X	X			X							
Trinity	X	X			X							
Brazos	X	X			X							
<i>Pacific Ocean tributaries</i>												
Colorado			X				X		X			

^dSee Table 10 for states included in the southwest region.

10.10 Northwest Region

The northwest region has the largest runoff of any region. However, most of the water resources are in the western part of the region, whereas the eastern part is expected to have rather critical water-related energy problems. These problems, as discussed in Ref. 6, are primarily associated with projections of large increases in water requirements for development of the area's shale oil and coal deposits. Considering the enormous coal deposits in the area and the fact that fossil-fired plants require less cooling water than do nuclear plants, nuclear energy centers do not appear to be likely candidates for the eastern part of this region.

The western part of the region should have sufficient water to meet both agricultural and industrial needs. The only two large load areas are around Seattle and in the Willamette Valley. Both the quantity and distribution of water resources are satisfactory for either dispersed plants or large energy centers.

A list of the larger rivers in this region is given in Table 20, and the map of Fig. 28 shows those rivers having an annual, 20-year low flow greater than 1500 cfs. Although the upper Snake River in eastern Idaho and western Wyoming is shown in Fig. 28, large irrigation uses and losses from the main channel reduce the flow below that required for energy centers for about 100 miles. The feasibility of large uses of water upstream of this break is questionable. The format used for Table 20 is similar to those for the east coast in that the Pacific Ocean tributaries are listed from north to south and inland rivers start with the river farthest upstream.

10.11 California-Great Basin Region

Most of the future cooling water for the power needs of California and perhaps the Great Basin area will have to be from the Pacific Ocean. Although the map of Fig. 29 and data of Table 21 list the Colorado and Sacramento Rivers, the Colorado is already committed to other purposes, and the California Water Project will divert between 4 and 5 million

Table 20. Water resources for the northwest region^d

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Gulf of Mexico tributaries (via Mississippi)</i>												
Missouri	X	X	X	X		X	X	X	X	X	X	
Yellowstone	X	X	X		X	X	X		X			
Bighorn	X				X							
<i>Pacific Ocean tributaries (via Puget Sound)</i>												
Puyallup	X				X							
Snohomish		X				X						
Skykomish	X				X							
Snoqualmie	X				X							
Stillaguamish	X				X							
Skagit	X	X	X		X	X	X		X	X		
Sauk	X				X							
Baker					X							
Nooksack	X				X							
<i>Pacific Ocean tributaries</i>												
Noh					X							
Quinnault	X				X							
Chehalis	X	X			X	X						
Columbia				X				X				X
Kootenay		X	X				X		X	X		
Pend Oreille			X	X				X		X		
Clark Fork	X	X	X		X	X		X		X		
Flathead	X	X	X		X	X	X		X			
South Fork Flathead	X				X							

Table 20 (continued)

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Pacific Ocean tributaries</i>												
Kettle	X				X							
Spokane	X	X			X	X						
Okanogan	X				X							
Wenatchee	X				X							
Yakima	X				X							
Snake	X	X	X	X	X	X	X	X			X	X
Payette					X							
Salmon	X	X			X	X	X		X			
Clearwater		X	X				X		X			
North Fork Clearwater	X				X	X						
Middle Fork Clearwater		X				X						
Loches					X							
Selkay	X				X							
Duschnutes	X				X	X			X	X		
Willamette	X	X	X	X		X	X	X	X	X		
Middle Fork Willamette	X				X							
McKenzie	X				X	X						
Sentem		X				X						
North Santiam	X				X							
South Santiam	X				X							
Clackamas	X				X							
Lewis	X				X	X						

Table 20 (continued)

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Pacific Ocean tributaries</i>												
Cowlitz	X	X			X	X	X		X			
Nehalem					X							
Umpqua		X				X						
North Umpqua	X				X							
South Umpqua					X							
Coquille	X				X							
Rogue	X	X			X	X						
Illinois	X				X							
<i>Hudson Bay tributary</i>												
Red	X											

^aSee Table 10 for states included in the Northwest region.

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Fig. 28. Rivers having an annual, 20-year low flow greater than 1500 cfs - northwest region.

Fig. 29. Rivers having an annual, 20-year low flow greater than 1500 cfs - California-Great Basin region.

Table 21. Water resources for the California-Great Basin region^a

River basins	River flow rates (cfs)											
	Mean annual flow				Annual, 20-year low flow				Monthly, 20-year low flow			
	3000- 6000	6000- 12,000	12,000- 24,000	>24,000	1500- 3000	3000- 6000	6000- 12,000	>12,000	1500- 3000	3000- 6000	6000- 12,000	>12,000
<i>Pacific Ocean tributaries</i>												
Smith	X				X							
Klamath	X	X	X		X	X	X		X			
Trinity	X				X							
Eel	X	X			X	X						
Sacramento		X	X	X		X	X	X	X	X	X	
Pit	X				X				X			
Feather	X	X			X	X						
American	X				X							
San Joaquin	X											
Colorado		X	X			X	X		X			
Green	X				X							

^aSee Table 10 for states included in the California-Great Basin region.

acre-ft of water per year from the Sacramento Delta to central and southern California, primarily for agricultural purposes. The northern California coastal rivers are rather small and far from the largest load centers, and the Great Basin area of Nevada and Utah already has water supply problems. The feasibility of large energy centers for this region will depend on finding coastal sites with acceptable seismic risk, the use of dry cooling systems, or obtaining rights to water currently being used for other purposes.

11. SUMMARY AND CONCLUSIONS

The quantity of water used for power plant cooling will be the same per unit of output for either large energy centers or small, dispersed plants. From a water resources viewpoint, the principal difference is the larger local water demand of energy centers, which restricts the potential sites for these centers to relatively large rivers.

The two criteria used for screening purposes to identify those rivers having sufficient flow to be of interest as potential water sources for energy centers emphasize the advantages of locating the centers on reservoirs. The 7-day, 10-year or monthly, 20-year low flow is about 10 to 20% of the mean annual flow for many U.S. rivers, whereas the annual, 20-year low flow is about 40 to 70% of the mean annual flow. Thus, the use of reservoirs to provide cooling water during periods of low seasonal flows will increase both the number of rivers that can support energy centers and the size of energy centers that can be located on the rivers. These differences are readily apparent from Figs. 17 and 18.

The mean annual runoff from the United States (48 states, excluding runoff from Canada) is about 1,860,000 cfs, and the annual, 20-year low runoff is about 1,100,000 cfs. The area of the 48 states is about 3×10^6 sq miles, and the mean annual runoff is then 0.62 cfs/sq mile and the annual, 20-year low runoff is 0.37 cfs/sq mile. These values can also be expressed as 8.4 and 5.0 in. per year respectively. Part of this runoff is in small coastal rivers that are too small to support energy centers, and part will be in areas that are unsuitable for other reasons. However, the mean annual flow from the three largest rivers (including runoff from Canada), the Mississippi-Atchafalaya, the Columbia, and the St. Lawrence, is 1,095,000 cfs. The annual, 20-year and the monthly, 20-year low flows for these three rivers are 750,000 and 435,080 cfs respectively.

The total installed electrical capacity projected for the United States in the years 2000 and 2020 is 1,575,000 and 3,000,000 MWe respectively. These correspond to the equivalent of 1312 and 2500 units

(1200-MWe). The cooling water requirements for this capacity, when considering the plant load factors, seasonal variations in water demand, and the mix of nuclear and fossil-fired plants, will average about 16 cfs/1200-MWe unit on an annual basis. The total cooling water requirements for these years will be about 21,000 and 40,000 cfs. In practice, part of this capacity will be provided by hydroelectric stations, and part will be cooled by seawater. The total fresh water requirements for power plant cooling need not place a serious burden on the total quantity of water available. Furthermore, some fraction of the water evaporated will be returned to the continent as additional precipitation downwind of the NECs, and part of this will show up as increased runoff to the various river basins.

An interesting manner in which one can analyze power requirements and also derive some insight as to the practicality of large energy centers is by the power density requirements, that is, the capacity required per square mile. For the year 2020, the projected power capacity of 3,000,000 MWe corresponds to 1 MWe/sq mile, and a 1200-MWe unit will serve an area of 1200 sq miles. If plants were placed on a rectangular pattern across the country, there would be one plant each 34.6 miles; the distance between energy centers of 4, 10, and 40 units would be 69, 110, and 219 miles respectively. The average annual cooling water consumption rate for a power capacity of 1 MWe/sq mile is about 0.18 in. per year, which is 2.1% of the mean annual flow and 3.6% of the annual, 20-year runoff for the United States.

Both the availability of water resources and the projected power capacity density vary widely across the country. The water resources east of the Mississippi River are plentiful. These resources include the Great Lakes, Atlantic Ocean, Gulf of Mexico, and most of the rivers in the country capable of supporting energy centers. The power density requirements in much of this area are extensive and well located in relation to the water resources for large energy centers. Some parts of the heavily populated eastern coastal areas have had water supply problems in recent years. However, these problems are primarily the result of inadequate development of available water resources rather

than a lack of resources. The southern part of Florida does not have sufficient fresh water supplies and will have to depend on seawater for power plant cooling.

Between the Mississippi River and the 97th meridian (a line between the eastern border of the Dakotas and Dallas, Texas), the water resources are much less plentiful. However, most of the larger load centers in this area are along or within a reasonable distance of the major rivers (Mississippi, Missouri, Arkansas, Red, or White) or the Gulf of Mexico and could be served from large energy centers.

The area of the country west of the 97th meridian, with the exception of the Pacific Northwest, has or will have water supply problems. There are only three large rivers in this area - the upper Missouri, Colorado, and Sacramento. The upper Missouri River region is expected to have critical water supply problems due primarily to projections of large increases in water requirements for the development of the region's shale oil and coal deposits. Because diversion of water from the lower part of the Colorado and Sacramento Rivers, primarily for agricultural purposes, is extensive, the outflow of these rivers is insufficient to support an energy center; therefore, any large utilization of water from these rivers for energy centers would be at the expense of other uses. The electrical loads and demand density in most of this area are small and not well suited to energy centers. The largest load centers are along the California coast, and the feasibility of supplying these loads from large energy centers will depend on finding coastal sites having acceptable seismic risk, using dry cooling systems, or obtaining rights to water currently being used for other purposes.

The Pacific Northwest should have sufficient water to meet both agricultural and industrial needs. The only two large load centers in this area are around Seattle and in the Willamette Valley. Both the quantity and distribution of water resources are satisfactory for either dispersed plants or large energy centers.

This study was not intended to discuss national or industrial priorities for water use. However, it is apparent that rather detailed long-range planning will be needed to resolve conflicting demands on water resources.

Appendix
TERMINOLOGY AND CONVERSION FACTORS

Hydrology, like most disciplines, has evolved its own terminology and, like other disciplines, has several sets of units to express quantities. This section defines some of the terms most commonly used in studies of water resources and provides conversion tables for the units most commonly used.

Hydrograph: A graph showing stage, flow, velocity, or other properties of water with respect to time.

Annual discharge hydrograph: A graph of mean daily discharge vs data for a one-year period (usually October 1 to September 30).

Average flow: The average discharge, usually expressed in cubic feet per second (cfs), for any specified period of time.

Annual average flow: The average discharge for any specific year.

Mean annual flow: The average of the available (recorded) annual average flows.

Runoff: That portion of the precipitation that ultimately reaches streams or rivers. Runoff is usually expressed in inches per unit of time (month or year). For a river basin, runoff is often expressed as cubic feet per second per square mile of drainage area (cfs/sq mile). The mean annual runoff for the United States east of the 100th meridian is about 1 cfs/sq mile.

Flow duration: The discharge, usually expressed in cfs or cfs/sq mile, that is equaled or exceeded a specific percent of the time; that is, the 90% duration flow is that which is equaled or exceeded 90% of the time. The 90% duration flow for the United States east of the 100th meridian is about 0.2 cfs/sq mile and for unregulated streams is about 20% of the mean annual flow.

Flow frequency: That discharge, averaged over some time period, that will recur at some specific time interval. This term can refer to either high or low flows and is expressed in many ways. For example, the 7-day, 10-year low flow is the lowest 7-day average discharge that will occur on the average of once every 10 years. The minimum annual average 7-day flow will be equal to or less than the 7-day, 10-year low flow at

intervals averaging 10 years in length, or the probability is 0.1 that the minimum average 7-day flow in any year will be equal to or less than the 7-day, 10-year low flow. Frequency curves, giving flow frequencies, often use average flow periods ranging from three days to one year and recurrence intervals from one to fifty years. For unregulated streams, the 7-day, 10-year low flow is about 10% of the mean annual flow.

Most of the data published in the USGS water supply papers provide flow data in cfs; however, studies intended for more general use give flows in other units, usually million gallons per day (Mgd). The following tables provide conversion factors for the more commonly used units of volume and flow rates.

Volumes

Cubic feet	Gallons	Acre-feet
1	7.48	2.30×10^{-5}
0.134	1	3.07×10^{-6}
43,560	3.26×10^5	1

Flow Rates

Cubic feet per second	Gallons per minute	Million gallons per day	Acre-feet per day
1	449	0.646	1.98
2.23×10^{-3}	1	1.44×10^{-3}	4.72×10^{-3}
1.55	694	1	3.07
0.505	226	0.326	1

REFERENCES

1. U.S. Nuclear Regulatory Commission, *Nuclear Energy Center Site Survey - 1975*, NUREG-0001, January 1976.
2. United States Water Resources Council, *The Nation's Water Resources*, U.S. Government Printing Office, Washington, D.C., 1968.
3. C. C. Burwell, *Water Pollution and Electricity Production: The Open Cycle Cooling Tower for Stream Aeration - A Preliminary Evaluation*, ORNL/TM-3979, Oak Ridge National Laboratory, Oak Ridge, Tenn., October 1972.
4. N. Wollman and G. W. Bonem, *The Outlook for Water*, The John Hopkins Press, Baltimore, Maryland, 1971.
5. U.S. Department of Agriculture, *The Yearbook of Agriculture 1955: Water*, U.S. Government Printing Office, Washington, D.C.
6. U.S. Water Resources Council, *Project Independence, Water Requirements, Availabilities, Constraints, and Recommended Federal Actions*, U.S. Government Printing Office, Washington, D.C., November 1974.
7. U.S. Environmental Protection Agency, *Proposed Criteria for Water Quality*, vol. I, U.S. Government Printing Office, Washington, D.C., October 1973.
8. United Engineers and Constructors, *Heat Sink Design and Cost Study for Fossil and Nuclear Power Plants*, WASH-1360, December 1974.
9. U.S. Water Resources Council, *1975 Water Assessment*, to be published.
10. Lower Mississippi Region Comprehensive Study Coordinating Committee, *Lower Mississippi Region Comprehensive Study*, Appendix C, vols. I and II, 1974.
11. Pacific Northwest River Basins Commission, *Columbia-North Pacific Region Comprehensive Framework Study*, Appendix V, vols. 1 and 2, Vancouver, Washington, April 1970.
12. U.S. Army Engineer Division, *Ohio River, Ohio River Basin Comprehensive Study*, Appendix C, Cincinnati, Ohio, August 1966.
13. Missouri Basin Inter-Agency Committee, *The Missouri River Basin Comprehensive Framework Study*, vol. 6, December 1971.
14. U.S. Atomic Energy Commission, *Nuclear Power Growth, 1974-2000*, WASH-1139, February 1974.