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Water Consumption by Nuclear Powerplants and Some Hydrological Implications

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By E. V. Giusti and E. L. Meyer

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ABSTRACT

About 63 percent of the energy input to a nuclear powerplant is discharged as heat to the cooling water system. Published data show that estimated water consumption varies with the cooling system adopted, being least in once-through cooling (about 18 cubic feet per second per 1,000 megawatts electrical) and greatest in closed cooling with mechanical draft towers (about 30 cubic feet per second per 1,000 megawatts electrical). When freshwater is used, this large variation carries important implications to the regional water resources economy in view of the increasingly keen competition for water. Thus it is felt that there is an urgent need to verify these findings with measurements.

The critical need for cooling water at all times by the nuclear powerplant industry, coupled with the knowledge that water withdrawal in the basin will generally increase with time and will be at a maximum during low-flow periods, indicates a need for reexamination of the design low flow currently adopted and the methods used to estimate it. In particular there is a need to develop models which account and evaluate low flows in terms of the ground-water inflow to the river basin network, the evapotranspiration from the basin, and the basinwide water consumption by man.

The amount of power generated, the name of the cooling water source, and the cooling method adopted for all nuclear powerplants projected to be in operation by 1985 in the United States are tabulated and the estimated annual evaporation at each powerplant site is shown on a map of the conterminous United States. Another map is presented that shows all nuclear powerplants located on river sites as well as stream reaches in the United States where the 7-day, 10-year low flow is at least 300 cubic feet per second or where this amount of flow can be developed with storage.

INTRODUCTION

The quest in the United States for self-sufficiency in energy, at some time in the future, is bound to elicit large increases in water demand. A good part of this demand for water will be directed to what is now the largest user of water in the Nation: the electric power industry. To the extent that nuclear powerplants will occupy a progressively larger share of the future electric power generation, the demand for water for cooling by this industry will increase vastly. The purpose of this paper is to document the water consumption by all nuclear powerplants envisioned in operation in the United States by 1985, to discuss some hydrological implications concerning freshwater consumption, and to provide some hydrologic information for planning the siting of powerplants along rivers.

WATER USE IN NUCLEAR POWERPLANTS

The production of electricity by nuclear powerplants involves, first, the transformation of the kinetic energy generated in the fission reaction into heat and, second, the conversion of this heat into stream and finally into electricity through turbine-driven generators. As shown by Hughes (1975), about one-third of the available thermal energy is converted into electricity; the remainder, as shown in figure 1, is expended as a direct loss to the atmosphere from the plant (5 percent) or is transmitted to the condenser cooling system (63 percent). The amount of water needed to cool the condenser varies with the amount of electricity generated as well as with the type of cooling system adopted. A theoretical estimate of the amount of water needed may be computed by equating the residual energy after electric generation, with the equivalent amount of energy that would be needed to evaporate water. The reasoning is as follows.

The amount of heat needed to evaporate water, its latent heat of vaporization, varies with temperature; it may be expressed as 1,040 Btu per pound of water at a temperature of about 70°F. Thus the amount needed to evaporate 1 cubic foot of water (62.3 pounds) is 65,000 Btu. Given that 1 Btu per second equals 1,055

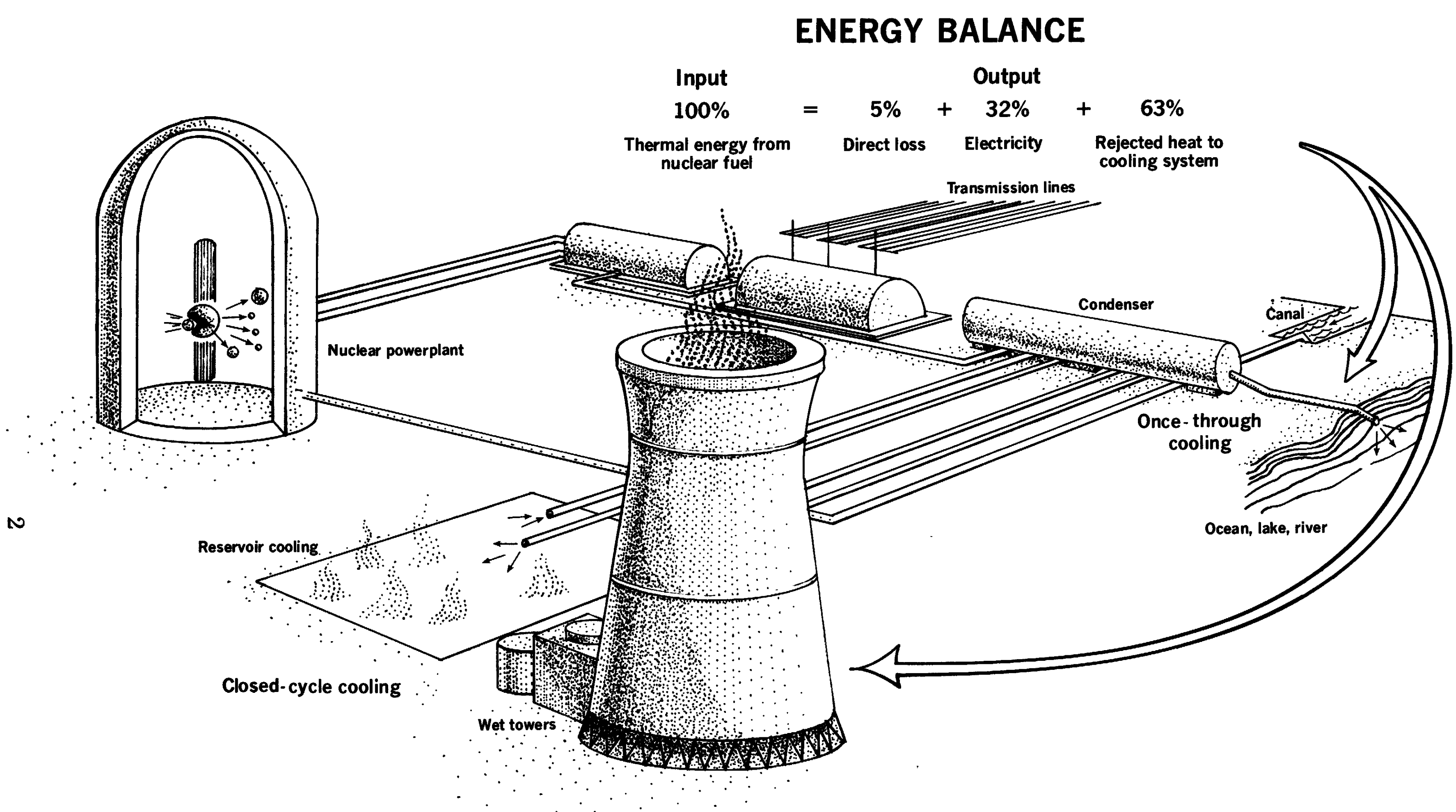

FIGURE 1.—Sketch showing energy balance and cooling systems of nuclear powerplants.

watts, it is concluded that about 69 MW (megawatts) are needed to evaporate a water flow of 1 ft^3/s (cubic foot per second). The energy balance of figure 1 shows that only 32 percent of the input energy is converted into electricity, and thus the production of 1,000 MW of electric energy requires an input of 3,120 MW of thermal energy. Also from figure 1 it is seen that 63 percent of this thermal energy (about 2,000 MW) is transmitted to the water cooling system. In terms of the equivalent evaporative energy previously computed (that is, 69 MW=1 ft^3/s evaporated water), the amount of cooling water required for a 1,000 MWe nuclear powerplant is about 29 ft^3/s.

The above calculations assume that all the rejected heat is dissipated by evaporation, whereas in practice some heat is dissipated by conduction and convection. For example, it is generally assumed (for example, Hughes, 1975) that cooling towers dissipate about 80 percent of the heat by evaporation and about 20 percent by conduction and convection through the air flowing through the towers. In this sense, less water would be consumed in the cooling process. However, with wet cooling towers, some water is lost as drift (that is, water drops carried by the rising air column), and some is lost in leaks, and so forth. In the end it is estimated in round numbers that about 25 ft^3/s would be consumed by a condenser cooling system with wet towers serving a 1,000 MWe plant.

The water cooling systems commonly used are shown in figure 1. In once-through cooling, water is circulated through the steam condenser once only and the heated water is discharged directly to the water body from which it was taken. In closed cooling systems, water is continuously recirculated through the condensers, and the cooling of the water is effected mainly through evaporation by means of towers, ponds, spray canals, and similar means. The water consumed is replaced with water taken from a water body (lake, river, or other water source). An additional small amount is taken and an equivalent small amount is continuously discharged to the water body to prevent an excessive buildup in the concentration of minerals in the circulating cooling water and to maintain steady-state conditions in the quantity and quality of water used in cooling. The water discharged into the water body is called blowdown. The water taken to replace that lost by evaporation and drift plus an amount equivalent to the blowdown is called makeup.

An analysis of cooling water consumption of nuclear powerplants has been made by the Directorate of Regulatory Standards of the U. S. Atomic Energy Commission (now the Nuclear Regulatory Commission) on the basis of data presented in the environmental impact reports prepared by the electric companies in connection with their applications for constructing and operating specific nuclear plants at specific sites (U. S. Atomic Energy Commission, 1974). The data cover most of the cooling systems in present use, and the evaporation for each cooling system was estimated for each specific site where a nuclear powerplant was proposed. Also, a series of plots was shown in which the estimated evaporation rates were correlated with the net electric power production for various cooling systems. A similar plot of these data is shown in figure 2, and a line is drawn for each identified cooling system. The slopes of the lines are as follows:

Mechanical draft wet towers	b = 0.031 or 31 $ft^3/s/1,000$ MWe
Natural draft wet towers	b = 0.029 or 29 $ft^3/s/1,000$ MWe
Cooling ponds (not including natural evaporation)	b = 0.021 or 21 $ft^3/s/1,000$ MWe
Once through	b = 0.018 or 18 $ft^3/s/1,000$ MWe

In comparison with theoretical computations based on latent heat of vaporization of water, the average slope for mechanical draft wet towers, that is 31 $ft^3/s/1,000$ MWe, slightly exceeds the 29 ft^3/s of evaporative energy previously computed. Furthermore, it should be pointed out that the 29 ft^3/s of evaporative energy computed from the latent heat of vaporization represents a maximum which assumes that all rejected heat is converted into evaporation, whereas only about 80 percent of it, or about 23 ft^3/s, is estimated to do so. It would appear thus that the data presented by the U. S. Atomic Energy Commission (1974) regarding water consumption by nuclear powerplants are somewhat conservative in that they overestimate the water consumption of the cooling

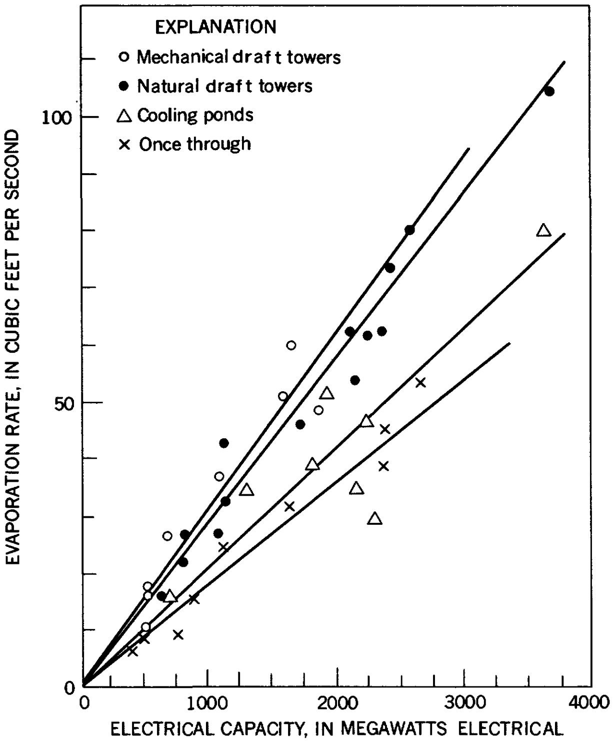

FIGURE 2.—Graph showing water consumption by nuclear powerplants.

process. In recognition of this, the electrical capacity data and the slope of the lines of figure 2 are used to estimate the total water consumption (rather than the cooling water consumption only) of all nuclear powerplants operating, in construction, or proposed in the United States through about 1985.

It is recognized, of course, that the data are derived from theoretical considerations and on the basis of unverified mathematical models of evaporation for the various cooling methods. Because of this it is felt that there is an urgent need to calibrate and verify the mathematical models in use with field measurements made at operating powerplants.

ANNUAL WATER CONSUMPTION

Data on the projected buildup of the nuclear powerplant industry through 1985 are available from various sources. The data considered in this paper consist of those published by the NUS Corporation (1974) plus data obtained directly from the Nuclear Regulatory Commission. The data given in table 1 consist of the names of all nuclear powerplants operating, under construction, and proposed for completion through 1985. The name of the water source for the plant, the cooling method employed, and the net electrical power generated are also given. While the location of the plants can be obtained roughly from table 1—the State and the water body concerned—a more accurate location of each plant was obtained and plotted on a map by West (1975). Figure 3, after West, has been modified to show the location of all the powerplants of table 1 as well as the urban centers of power consumption.

In order to estimate the annual water consumption for each plant, the relationships defined in figure 2 for the various cooling systems were used. The appropriate slope values are multiplied by the given net electrical power shown in table 1 to obtain the total water consumption for cooling. It should be noted that these data represent the net evaporation arising from cooling only and do not include water amounts used in plants, for other operations such as boiler feed, domestic use, and irrigation of plant grounds as well as water losses from leaks, seepage, drift, and so forth. However, the amounts of water involved for these purposes are small and are ignored here especially since the amounts of cooling water computed from figure 2 are thought to be somewhat high.

The evaporation rates of figure 2 must be increased if cooling ponds are used. In cooling ponds the natural evaporation from the water surface must be assessed. An estimate of this evaporation can be computed from data given by the U. S. Atomic Energy Commission (1974). The area of cooling ponds of selected powerplants is plotted in figure 4 versus the electrical capacity of the plants. The ordinate on the right side of this figure shows an estimate of the natural pond evaporation. It was scaled by assuming various net annual evaporation rates taken from maps prepared by Kohler, Nordenson, and Baker (1959) and is considered applicable for those regions where it is proposed to use artificial ponds for cooling nuclear powerplants. This graph was used together with that of figure 2 to estimate the total water consumption of those nuclear powerplants which adopt closed cycle cooling systems utilizing ponds or lakes built for this purpose.

A map of annual water consumption by nuclear powerplants is shown in figure 5. The data

TABLE 1.—*Selected data on nuclear powerplants in the United States which are operating, in construction, or proposed through about 1985*

Units and status: Number of letters equals number of units in given status: O=operating, C=construction, P=proposed

Cooling (method): CT=cooling towers (natural draft), Once=once-through cooling, RS=cooling pond, MCT=mechanical cooling towers, SP=spray canal or pond, Mixed=combination of cooling methods, usually once through and wet cooling towers

Item	Name	Units and status	State	Cooling Source	Cooling Method	Power (net Σ MWe)	Remarks
1	Allen's Creek	PP	Tex	Brazos River	RS	2,300	
2	Arkansas	O,C	Ark	Arkansas River	Once	1,762	
3	Atlantic	PPPP	N.J.	Atlantic Ocean	Once	4,600	
4	Bailly	C	Ind	Lake Michigan	CT	660	
5	Barton	PPPP	Ala	Coosa River	MCT	4,636	
6	Beaver Valley	CC	Pa	Ohio River	MCT	1,704	
7	Bellefonte	PP	Ala	Reservoir on Tennessee River	CT	1,800	
8	Big Rock Point	O	Mich	Lake Michigan	Once	75	
9	Black Fox	CC	Okla	Verdigris River	MCT	1,900	
10	Blue Hills	PP	Tex	Sabine River	MCT	1,836	
11	Braidwood	PP	Ill	Kankakee River	RS	2,240	
12	Browns Ferry	OO,C	Ala	Lake Wheeler	Once	3,195	Mixed cooling method in future.
13	Brunswick	CC	N.C.	Cape Fear Estuary	Once	1,642	Do.
14	Byron	PP	Ill	Rock River	CT	2,240	
15	Callaway	PP	Mo	Missouri River	CT	2,300	
16	Calvert Cliffs	OO	Md	Chesapeake Bay	Once	1,690	
17	Catawba	PP	S.C.	Lake Wylie	Once	2,306	
18	Cherokee	PPP	S.C.	Broad River	MCT	3,840	
19	Clinch River	P	Tenn	Clinch River	MCT	350	Breeder Reactor Plant.
20	Clinton	PP	Ill	Salt Creek	RS	1,910	
21	Comanche Peak	PP	Tex	Squaw Creek Reservoir	RS	2,300	
22	Cook	O,C	Mich	Lake Michigan	Once	2,120	
23	Cooper	O	Nebr	Missouri River	Once	778	
24	Crystal River	O	Fla	Gulf of Mexico	Once	825	
25	Davis Besse	C,PP	Ohio	Lake Erie	CT	2,718	
26	Diablo Canyon	CC	Calif	Pacific Ocean	Once	2,190	
27	Douglas Point	PP	Md	Potomac River	CT	2,356	
28	Dresden	OOO	Ill	Illinois River	RS	1,818	
29	Duane Arnold	O	Iowa	Cedar River	CT	569	
30	Farley, J.	CC	Ala	Woodruff Reservoir	MCT	1,658	
31	Fermi	C,P	Mich	Lake Erie	Mixed	2,303	
32	Fitzpatrick	O	N.Y.	Lake Ontario	Once	821	
33	Forked River	C	N.J.	Barnegat Bay	CT	1,070	
34	Fort Calhoun	O	Nebr	Missouri River	Once	457	
35	Fort St. Vrain	O	Colo	South Platte River	MCT	330	
36	Fulton	PP	Pa	Susquehanna River	CT	2,280	
37	Ginna	O	N.Y.	Lake Ontario	Once	490	
38	Grand Gulf	PP	Miss	Mississippi River	CT	2,580	
39	Greenwood	PP	Mich	Lake Huron	SP	2,400	
40	Haddam Neck	O	Conn	Connecticut River	Once	575	
41	Hanford	O	Wash	Columbia River	CT	850	
42	Hartsville	PPPP	Tenn	Cumberland River	CT	4,820	
43	Hatch Edwin	O,C	Ga	Altamaha River	MCT	1,581	
44	Hope Creek	PP	N.Y.	Delaware Estuary	CT	2,134	
45	Humboldt Bay	O	Calif	Humboldt Bay	Once	63	
46	Indian Point	OO,C	N.Y.	Hudson Estuary	Once	2,103	
47	Jamesport	PP	N.Y.	Long Island Sound	Once	2,300	
48	Kewaunee	O	Wis	Lake Michigan	Once	541	
49	Koshkonong	PP	Wis	Lake Koshkonong	CT	1,800	
50	LaCrosse	O	Wis	Mississippi River	Once	50	
51	LaSalle	CC	Ill	Kankakee River	RS	2,156	
52	Limerick	CC	Pa	Schuykill River	CT	2,130	
53	Maine Yankee	O	Maine	Back River Estuary	Once	790	
54	McGuire	CC	N.C.	Lake Norman	Once	2,360	
55	Midland	CC	Mich	Saginaw River	RS	1,310	
56	Millstone	O,C,P	Conn	Niantic Bay	Once	2,639	

TABLE 1.—*Selected data on nuclear powerplants in the United States which are operating, in construction, or proposed through about 1985*—Continued

Item	Name	Units and status	State	Cooling Source	Cooling Method	Power (net Σ MWe)	Remarks
57	Montague	PP	Mass	Connecticut River	CT	2,300	
58	Monticello	O	Minn	Mississippi River	Mixed	545	
59	Nine Mile Pt	O,C	N.Y.	Lake Ontario	Once	1,705	
60	Norco	P	P.R.	Atlantic Ocean	Once	583	
61	North Anna	CCCC	Va.	North Anna Reservoir	RS	3,610	
62	Oconee	OOO	S.C.	Lake Keowee	Once	2,658	
63	Oyster Creek	O	N.J.	Barnegat Bay	Once	640	
64	Palisades	O	Mich	Lake Michigan	Mixed	700	
65	Palo Verde	PPP	Ariz	Phoenix Sewage	MCT	3,810	
66	Peach Bottom	OOO	Pa	Lake Conowingo	MCT	2,170	
67	Pebble Springs	PP	Oreg	Columbia River	RS	2,520	
68	Perkins	PPP	N.C.	Yadkin River	MCT	3,840	
69	Perry	PP	Ohio	Lake Erie	CT	2,410	
70	Pilgrim	O,C	Mass	Cape Cod Bay	Once	1,844	
71	Point Beach	OO	Wis	Lake Michigan	Once	994	
72	Prairie Island	OO	Minn	Mississippi River	MCT	1,060	
73	Quad Cities	OO	Ill	Mississippi River	Once	1,600	
74	Rancho Seco	O	Calif	American River	CT	804	Irrigation Canal.
75	River Bend	PP	La	Mississippi River	MCT	1,868	
76	Robinson	O	N.C.	Lake Robinson	Once	700	
77	Salem	CC	N.J.	Delaware Estuary	Once	2,205	
78	San Joaquin	PPPP	Calif	Calif. Aqueduct	CT	5,200	Possibly MCT.
79	San Onofre	O,CC	Calif	Pacific Ocean	Once	2,710	
80	Seabrook	PP	N.H.	Atlantic Ocean	Once	2,400	
81	Sequoyah	CC	Tenn.	Lake Chickamauga	Once	2,240	Also CT in future.
82	Shearon Harris	PPPP	N.C.	Cape Fear River	Mixed	3,660	
83	Shoreham	C	N.Y.	Long Island Sound	Once	819	
84	Skagit	PP	Wash	Skagit River	CT	2,554	
85	Somerset	PP	N.Y.	Lake Ontario	CT	2,440	
86	South Texas	PP	Tex	Colorado River	RS	2,500	
87	St. Rosalie	PP	La	Mississippi River		2,320	Not yet decided.
88	Summer	C	S.C.	Lake Monticello	RS	900	
89	Summit	PP	Del	Chesapeake-Delaware Canal	MCT	1,540	
90	Surry	OO,PP	Va	James River Estuary	Mixed	3,294	
91	Susquehanna	CC	Tenn	Susquehanna River	CT	2,100	
92	Sterling	P	N.Y.	Lake Ontario	Once	1,150	
93	St. Lucie	CC	Fla	Atlantic Ocean	Once	1,610	
94	Three Mile Is.	O,C	Pa	Susquehanna River	CT	1,724	
95	Trojan	C	Oreg	Columbia River	CT	1,130	
96	Turkey Point	OO	Fla	Biscayne Bay	Mixed	1,386	
97	Tyrone	PP	Wis	Chippewa River	MCT	2,300	
98	Vermont Yankee	O	Vt	Connecticut River	Mixed	514	
99	Vidal	PP	Calif	Colorado River	CT	1,540	
100	Vogtle A.W.	CCCC	Ga	Savannah River	CT	4,452	
101	Waterford	P	La	Mississippi River	Once	1,113	
102	Watts Bar	CC	Tenn	Chickamauga Lake	CT	2,338	
103	Wolf Creek	P	Kans	Neosho River	RS	1,150	
104	WPPSS 1 & 4	PP	Wash	Columbia River	MCT	2,412	
105	WPPSS 3 & 5	PP	Wash	Chehalis River	CT	2,484	
106	Yankee-Rowe	O	Mass	Lake Sherman	Once	175	
107	Zimmer	C,P	Ohio	Ohio River	CT	1,980	
108	Zion	OO	Ill	Lake Michigan	Once	2,100	

represent the plants listed in table 1 and located in the map of figure 3. The water consumption is expressed as an average rate which would be applicable for those parts of the year when the plant is operating. It would be possible, of course, to reduce the amounts shown by some percentage according to the past experience regarding the percentage of time that nuclear powerplants have been in operation. In design, it is often assumed that plants operate 80 percent of the time, but in practice the percentages have so far been lower. It was felt, how-

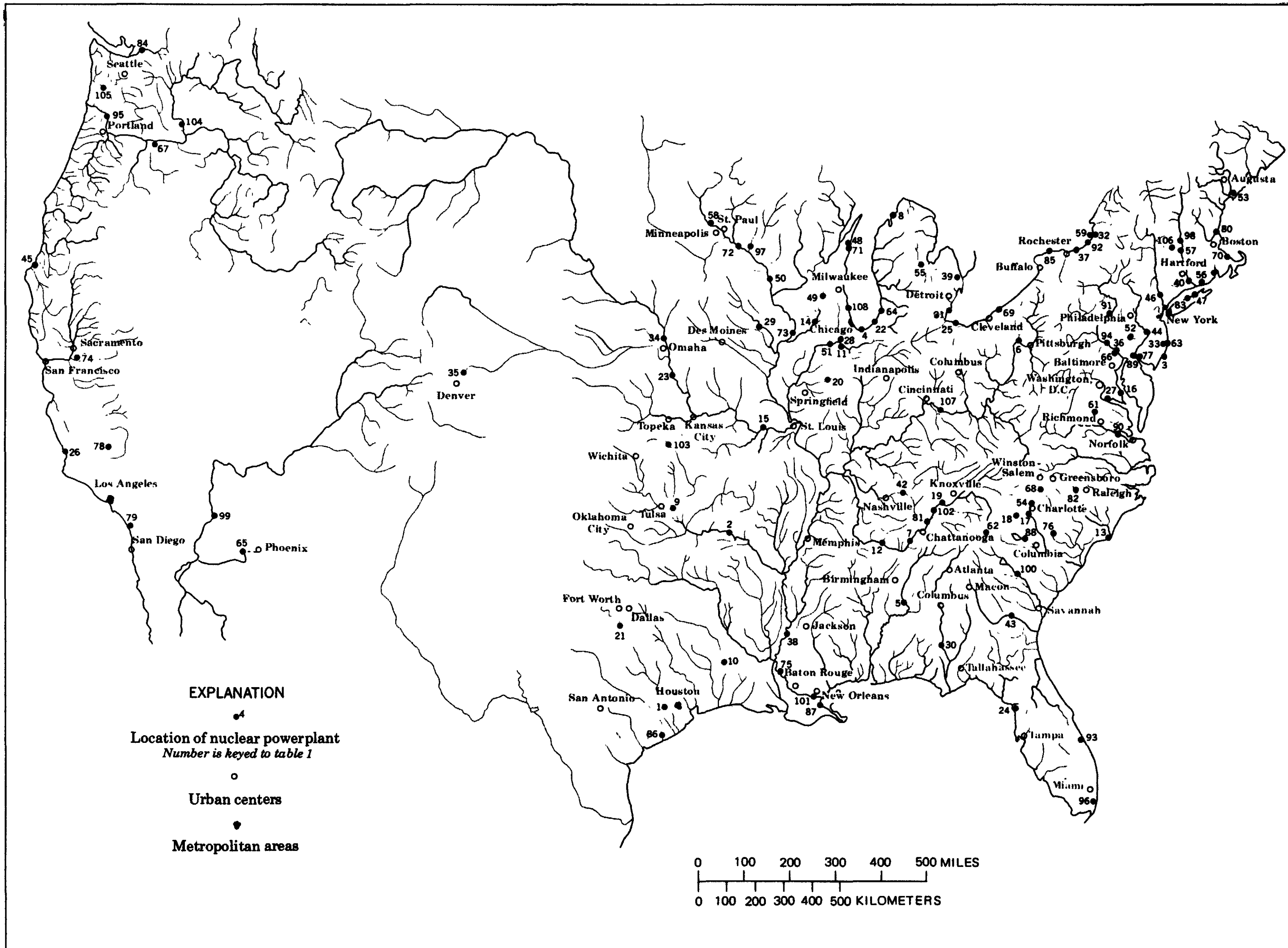

FIGURE 3.—Map showing location of nuclear powerplants in the conterminous United States.

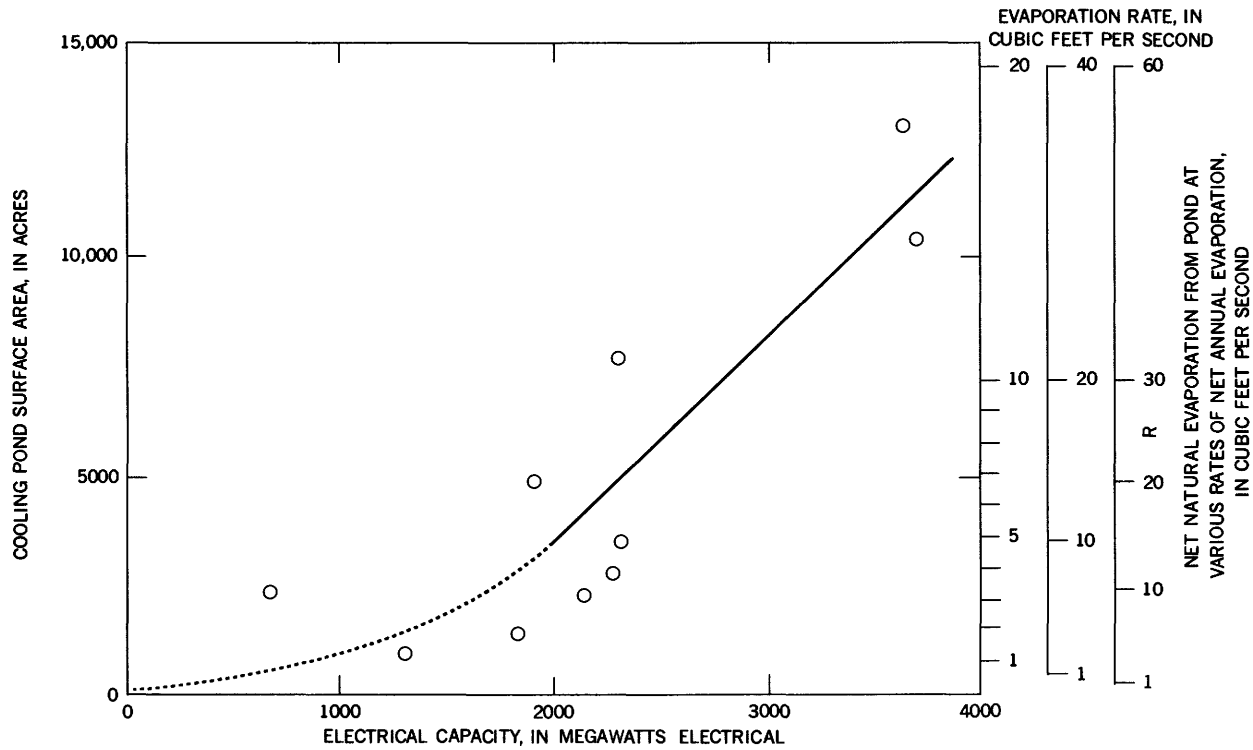

FIGURE 4.—Graph showing relationship between cooling pond surface area and plant's electrical capacity.

ever, that to take this into account would have introduced an additional variable into the picture, and thus figure 5 should be viewed as showing the maximum average rates of water consumption.

It is believed that the data of figure 5 provide basic information and guidance for water-resource managers as well as nuclear power-plant planners, regarding the siting of additional water consuming industry, particularly on rivers. It is understood, of course, that the data presented concern only nuclear power-plants and thus represent only part of the water-consumption picture of each river basin.

As stated previously, estimates given are based on theoretical computations of evaporation rather than on field data. This should not detract from the usefulness of the data shown in figure 5 if it is considered that they represent a first approximation subject to some error, possibly of overestimation. However, because the siting of nuclear powerplants on inland stream sites, and particularly those plants using good quality freshwater for cooling, is inherently related to competition for available water, planners should have at hand realistic data regarding evaporation rates from the various cooling systems in use. Such data can only be obtained by field measurements.

STREAMFLOW CONSTRAINTS ON WATER CONSUMPTION FOR COOLING

An inspection of the data listed in table 1 or plotted on figure 3 shows that many plants are located on sites next to streams. These plants draw water directly from the streams without provision of significant storage. A consideration related to plant siting along rivers concerns periods of low streamflow when the impact on water resources of total water consumed in the cooling process is at a maximum. This consideration is particularly relevant for those plants which do not use cooling ponds with a sufficiently large storage capacity to allow within-pond recirculation of water for several days without intake from or discharge to the stream. Estimates of low flow of streams for plants withdrawing water for cooling continuously are particularly important and require careful definition for the following reason:

1. Safety. The regulatory staff of the U.S.

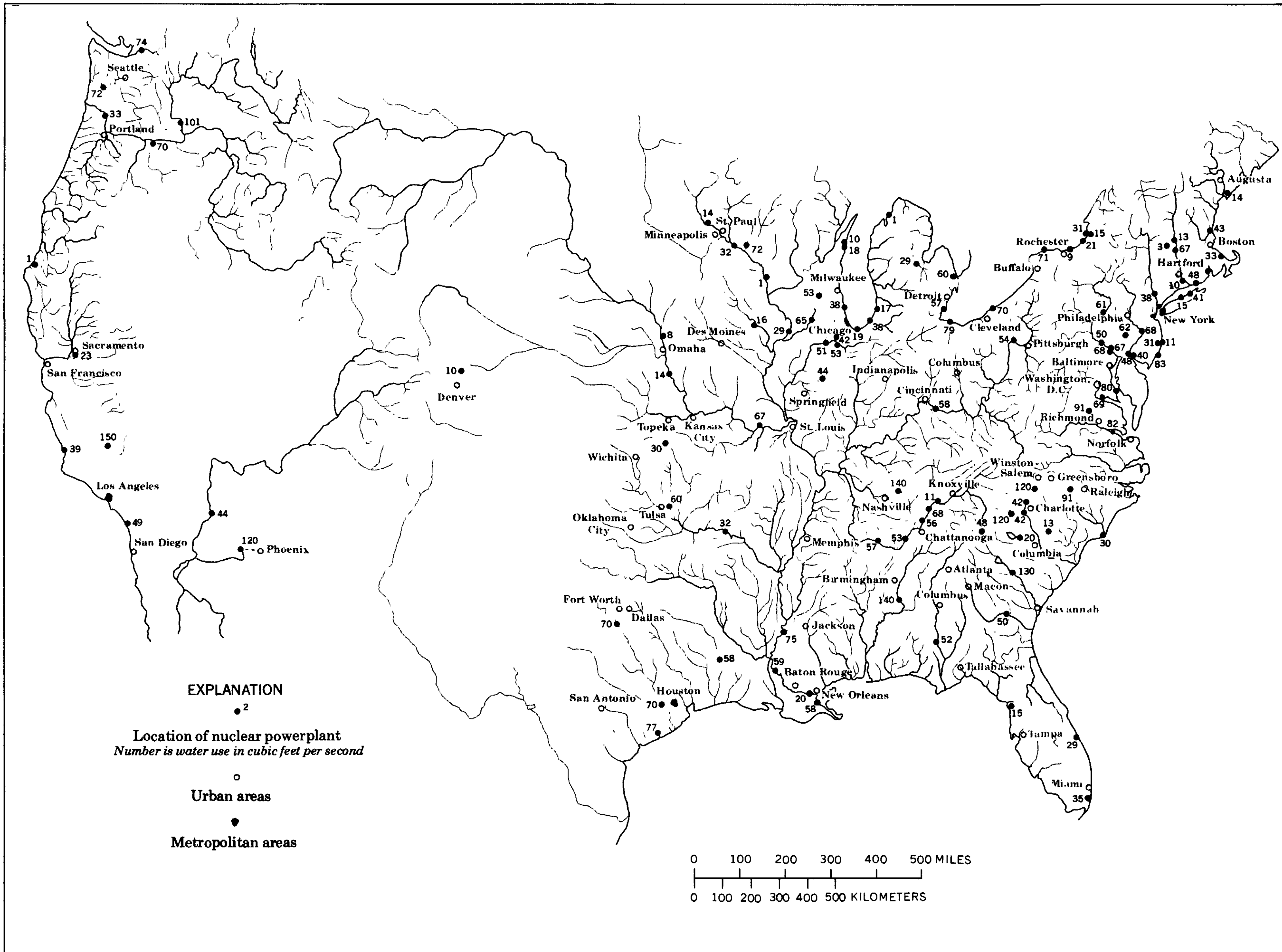

FIGURE 5.--Map showing water consumption by nuclear powerplant in cubic feet per second.

Atomic Energy Commission (1972) in reference to safety analysis reports for nuclear power plants states: "estimate the probable minimum flow rate*** resulting from the most severe drought considered reasonably possible in the region as such conditions may affect*** the ability of the ultimate heat sink to perform adequately***."

2. Standards. Most States have issued standards regarding the maximum permissible mineral concentration in surface waters to be used for cooling. As is well known, this concentration is at a maximum during low-flow periods because then the flow consists of ground-water discharge which is normally more concentrated mineralogically than surface water. Additional concentration of the streamflow mineral content is brought about by basin evapotranspiration which is also at a maximum during low-flow periods.
3. Ecology. Maximum ecological impact on freshwater biota can occur on some streams during low-flow periods if the mineral concentration exceeds certain limits or if the flow is abruptly reduced by withdrawal at powerplants. Furthermore, the withdrawal itself entails loss of biota by physical entrainment on the intake screens or by physical injury on passage through the water pumps.
4. Plant operation. The conditions described above may be such as to force the shutdown of the plant, with contingent costs and loss of revenue to the plant operators and loss of service to consumers. While this may be considered an acceptable operational rule under exceptional circumstances, say once in 10 years, it becomes a serious problem of misdesign when recurring more often, say once every year.

Because the streamflow constraints imposed on the siting of a nuclear powerplant can be severe under some circumstances, the estimation of low flow is an extremely important aspect of site planning. At the same time, it is also an aspect of hydrologic analysis which is pervaded with uncertainty and complexity. This uncertainty arises from several considerations as brought out in the following discussion.

The low streamflow observed at any river site represents ground-water discharge from upstream save for losses due to:

1. Evapotranspiration from ground-water reservoirs upstream from the observation point.
2. Ground water originating upstream from the observation point but emerging downstream from it (underflow), or outside the basin.
3. Upstream water withdrawal returned to the stream below the observation point.
4. Out-of-basin water transfer.
5. Within-basin consumptive use of water.

Although low-flow analysis is a multidisciplinary problem, involving in part surface-water hydrology, hydrogeology, and climatology, it has been dealt with, traditionally, as a surface-water problem through hydrograph analysis. From the practical point of view of engineering design, the frequency analysis of drought flow allows the analyst to choose that discharge and associated probability of occurrence that he feels to be appropriate to the problem at hand. Thus, for example, the so-called 7-day, 10-year low flow is used in evaluating environmental impacts to stream biota in the environmental impact statements of nuclear powerplants. It is interesting to note that hydrologists have resorted to the 7-day average low flow to smooth out or filter fluctuating hydrologic data such as that originating from rivers on which water-consuming activities might be shut down on weekends. In this respect it may also be noted that while the 7-day average low-flow index was devised for purposes of hydraulic design it has been retained also for assessing impacts on river biota. Clearly, however, for some rivers in which there is both a large fluctuation of instantaneous flow from day to day and a critical pollution level, environmental assessment based on the 7-day average flow may be misleading. In these rivers serious biological impacts may occur if the instantaneous flow during a 7-day low-flow period falls below a critical threshold even though the average during the 7-day period may not be particularly worrisome. The same kind of reasoning can be followed with respect to the chosen probability of occurrence (or return period) if the low-flow frequency curve is steep, that is if low flows decrease rapidly with decreasing return period. As an example one can postulate a situation in which a stream may have a low flow with a 10-year frequency which is acceptable for a given problem while the low flow with a 15-year frequency is not.

The choice of an appropriate low-flow index becomes particularly significant in the design of nuclear powerplants which require that a continuous source or reservoir of emergency cooling water be available to prevent major accidents even after shutdown. This is well recognized in the licensing regulations which stipulate that the probable minimum flow of streams providing cooling water be estimated and alternative sources provided for the time when the instantaneous flow could fall below the amount required for emergency cooling.

By desire or coincidence the probable minimum flow (pmf?) is analogous to the probable maximum flood (PMF), at least euphoniously. The latter has become well entrenched in usage, notwithstanding the existing disagreement between those who propound its use (determinists) and those who prefer a probabilistic approach to flood-level assessment. The former, the probable minimum flow, which is requested in the preparation of Preliminary Safety Analysis Reports for nuclear powerplants, is at present no more than a term, and there are no widely accepted standards for defining or calculating it.

Conceptually the probable maximum flood derives from meteorological arguments and is defined as follows by the World Meterological Organization (1974): "The probable maximum flood is that flood estimated to result if the most critical combination of severe meteorological and hydrological conditions considered reasonably possible in the region were to occur." Although the probable minimum flow would derive from hydrogeological and climatological arguments, H. C. Riggs (written commun., 1975) pointed out that the probable minimum flow would be a viable concept only for natural streams free of man's effects, and in times of severe droughts even these streams would not be free from emergency diversions. Taking this into consideration, the probable minimum flow may be defined in a manner similar to that of the probable maximum flood:

> The probable minimum flow is that flow estimated to result if the most critical combination of severe climatological and hydrogeological conditions considered possible in the region were to occur. For natural streams the probable minimum flow may be defined as the ground-water discharge to the network of stream channels, assuming water depletion in the soil and weathered rock, minus evapotranspiration from the basin. For stream basins subject to significant regulations or diversions, the probable minimum flow includes abstractions due to water consumption or interbasin water transfer taking place upstream from the river reach under study.

While it is recognized that the hydrogeologic limiting conditions given above for natural streams are somewhat arbitrary, they were derived from a study by Kilpatrick (1963) in which direct field observations of sources of base flow to a stream were made in a trench dug across the flood plain of a small stream in the Piedmont Province in Georgia. In this study it was observed that low flow in the dry season was derived entirely from the underlying rock aquifer as ground water in the soil and that the colluvium was exhausted.

Given this definition of the probable minimum flow, even if subject to modifications, there remains the task of computing it. Because no operational methods for computing the probable minimum flow exist, the matter is still at the research stage. Progress in deriving an acceptable computational method can be expected to emerge from mathematical modeling of the hydrogeologic, climatologic, and water-resources components which control the magnitude of the low flow. Of the above components the hydrogeologic one may be treated by classical deterministic methods used in ground-water-flow analysis, and the water-resources component involves accounting of consumptive uses by man. Finally the climatologic component involves consideration of the rates of evapotranspiration from the basin as well as determination of the most severe regional drought considered possible in the region. In the end the model should be able to match the dry season portion of streamflow hydrographs with sufficient reliability to serve as a predictor of the probable minimum flow. It would be expected that the calculated value be checked with regional values of extreme low flows determined by frequency analysis.

The view held here, which is implicitly embodied in the definition given above of the minimum probable flow, is that ground water is a conservative element of the total water cycle of natural stream basins and that its seasonal fluctuations within the year are small when compared to those of streamflow. In addition it is believed that the large variations of low flow

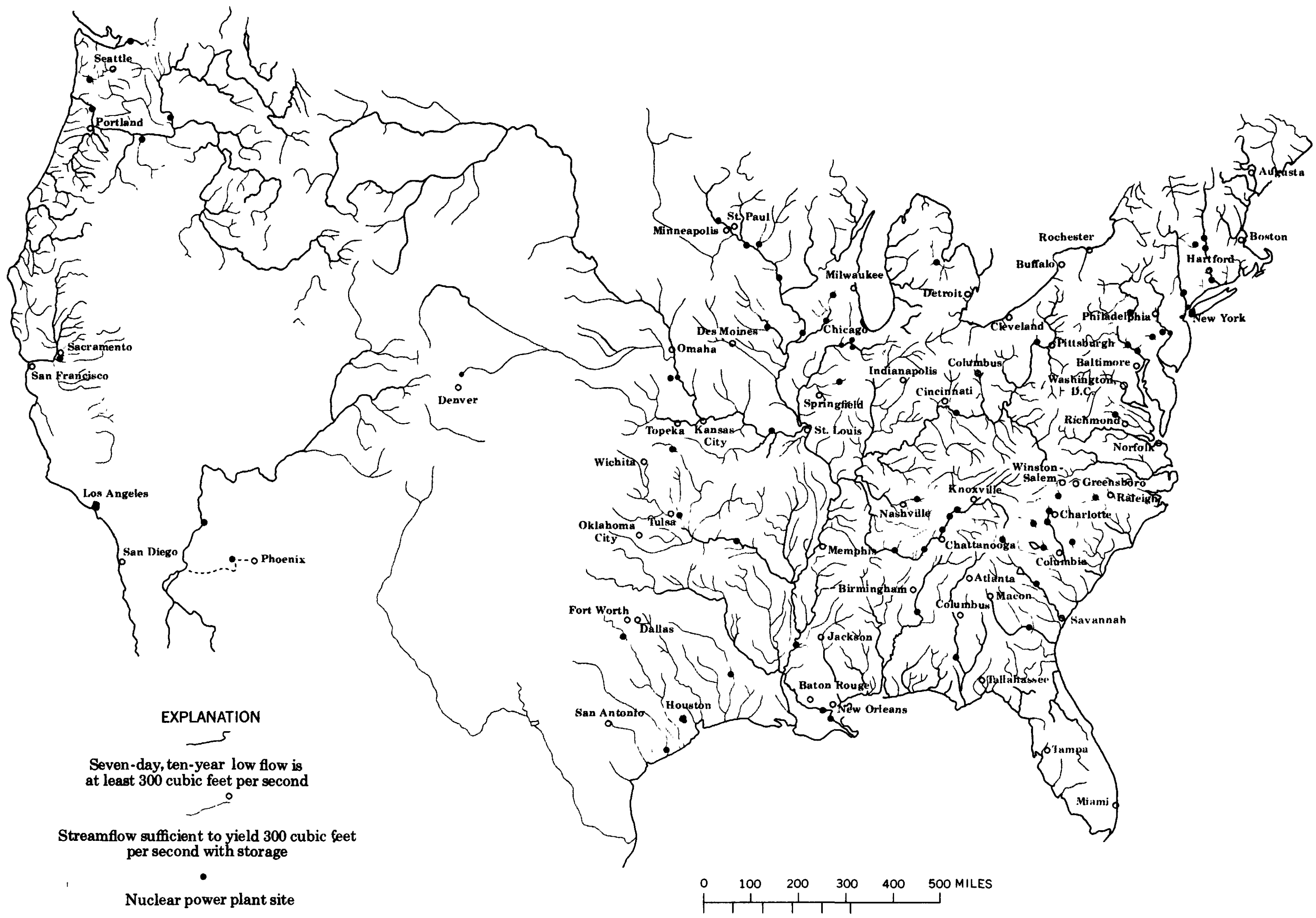

FIGURE 6.—Map showing stream reaches where the low flow is at least 300 cubic feet per second.

from year to year arise mainly from climatological variability. In the end, the assessment of the probable minimum flow in natural streams will rest on the assessment of "the most*** severe climatological*** conditions considered possible in the region."

SELECTED LOW-FLOW DATA IN THE CONTERMINOUS UNITED STATES

Stankowski, Limerinos, and Buell (1976) have examined the low flow in the conterminous United States for the purpose of providing a general appraisal of potential sites for cooling water. A map prepared by them identifies those streams for which the average 7-day low flow with a recurrence interval of 10 years is at least 300 ft^3/s. Their map also portrays those stream reaches which could sustain a flow of 300 ft^3/s if adequate storage were provided.

An adaptation of this map is shown in figure 6 together with the location of those powerplants which use streamflow as sources of cooling water. Although the choice of 300 ft^3/s as a flow index was arbitrary, it provides preliminary information for investigating the potential siting of powerplants. For 1,000 MWe plants, the low-flow index is conservative since water consumption in these plants would be at most (with wet mechanical draft cooling towers) about 30 ft^3/s, or 10 percent of the flow. For larger powerplants the data of figure 6 would have to be used with some judgment and interpretation, especially in view of the discussion of the previous section.

The information given in figure 6, the location of all powerplants using rivers as sources of cooling water (table 1), and also the water consumption data shown in figure 5 can serve as a first point of reference for plant siting. The next step, from a hydrological point of view, and in line with the previous discussion concerning low flow, should be the computation of the minimum streamflow to be expected in the given stream basin, taking into account present and future water withdrawals throughout the basin and making some allowance for possible emergency withdrawals during severe droughts.

CONCLUSIONS

Theoretical computations of water consumption by nuclear powerplants for cooling indicate that it is very large and varies greatly among the various cooling systems, being least in once-through cooling (18 ft^3/s per 1,000 MWe) and greatest in closed cooling via mechanical draft cooling towers (30 ft^3/s per 1,000 MWe).

Plants utilizing nonestuary seawater for cooling are not expected to have problems with the availability of water. Also, no hydrological problems regarding water quantity are foreseen for plants utilizing freshwater in large rivers and estuaries, even though environmental considerations have already brought about the preferential use of closed-cycle cooling which consumes more water than once-through cooling.

Problems of water scarcity are expected to arise, however, during low-flow periods in some small- or medium-sized basins (say, where low flows are less than 300 ft^3/s), especially where competing water demands exist now or are likely to emerge in the future. It appears that in the siting of nuclear powerplants in medium- and small-sized basins the relationship between water consumption and cooling method should be thoroughly evaluated with respect to the minimum streamflow expected to occur.

Because the data available on evaporation by various cooling methods are derived theoretically, there is an urgent need to verify these data with field measurements at operating plants. An equally urgent need exists to derive an operational model for the computation of the probable minimum flow.

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