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A TEST SIMULATION OF POTENTIAL EFFECTS OF THERMAL POWER PLANTS ON STREAMS IN THE UPPER MISSISSIPPI RIVER BASIN

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A TEST SIMULATION OF POTENTIAL EFFECTS OF THERMAL POWER PLANTS ON STREAMS IN THE UPPER MISSISSIPPI RIVER BASIN

by

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ABSTRACT

The 1964 thermal regimen of the Upper Mississippi River and eight major tributary streams were simulated with the COL HEAT digital model. The potential impact of 1980 and year 2000 power requirements were simulated under the assumption of flow through cooling of steam generating plants. The results indicate that by the year 2000 few, if any, plant sites will remain along the Mississippi River where flow through cooling can be exclusively utilized for 1,000 MW units.

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INTRODUCTION

The continued increase in demand for electrical energy by industrial and domestic users in the Mississippi Valley at rates estimated to be greater than 6 percent, compounded annually, up to the year 1990 has created a need for an examination of the environmental effects of the plant operations that will be required to satisfy the demand.

In view of this need, the Environmental and Sanitary Engineering Branch, Division of Reactor Development and Technology, U. S. Atomic Energy Commission, requested that Battelle-Northwest undertake a reconnaissance study of the potential effects of thermal power plants on river temperatures in the Upper Mississippi Basin. The primary purpose of the study was to test whether a regional simulation system, which was developed at the Pacific Northwest Laboratory to simulate the thermal regimen of the Columbia River, could also be applied to other locations in the United States.

This report summarizes the results of the study, the simulation of the 1964 thermal regimen of the Mississippi River between St. Cloud, Minnesota and Alton, Illinois. Simulations of eight major tributary streams are also included (see Figure 1 - the reaches simulated in this study are indicated in bold form). The potential effects of thermal loads on the system for the years 1970, 1980 and 2000 were simulated by utilizing Federal Power Commission forecasts of power requirements for the Upper Mississippi Power Region.

The results of this study depend quite heavily on the forecasts of electrical power development being prepared by the Federal Power Commission for the drainage area under study. Because of this, much material used has been directly taken from the report, "Upper Mississippi River Basin Comprehensive Study," Appendix M, POWER, Draft 3, prepared by the Chicago Office of the Federal Power Commission and the UMBR Power Advisory Committee and Industry Consultants. The acquisition and use of a reference copy of the Federal Power Commission report is advisable for a fuller understanding of the plant projections which are referenced in summary form in the present report.

Other reported uses of the Battelle developed simulation system include studies of the Deerfield River in Massachusetts,(2) the Upper Illinois River to mile 230,(3) and the regional investigations on the Columbia River for the Division of Production and the Division of Reactor Development and Technology.(1)

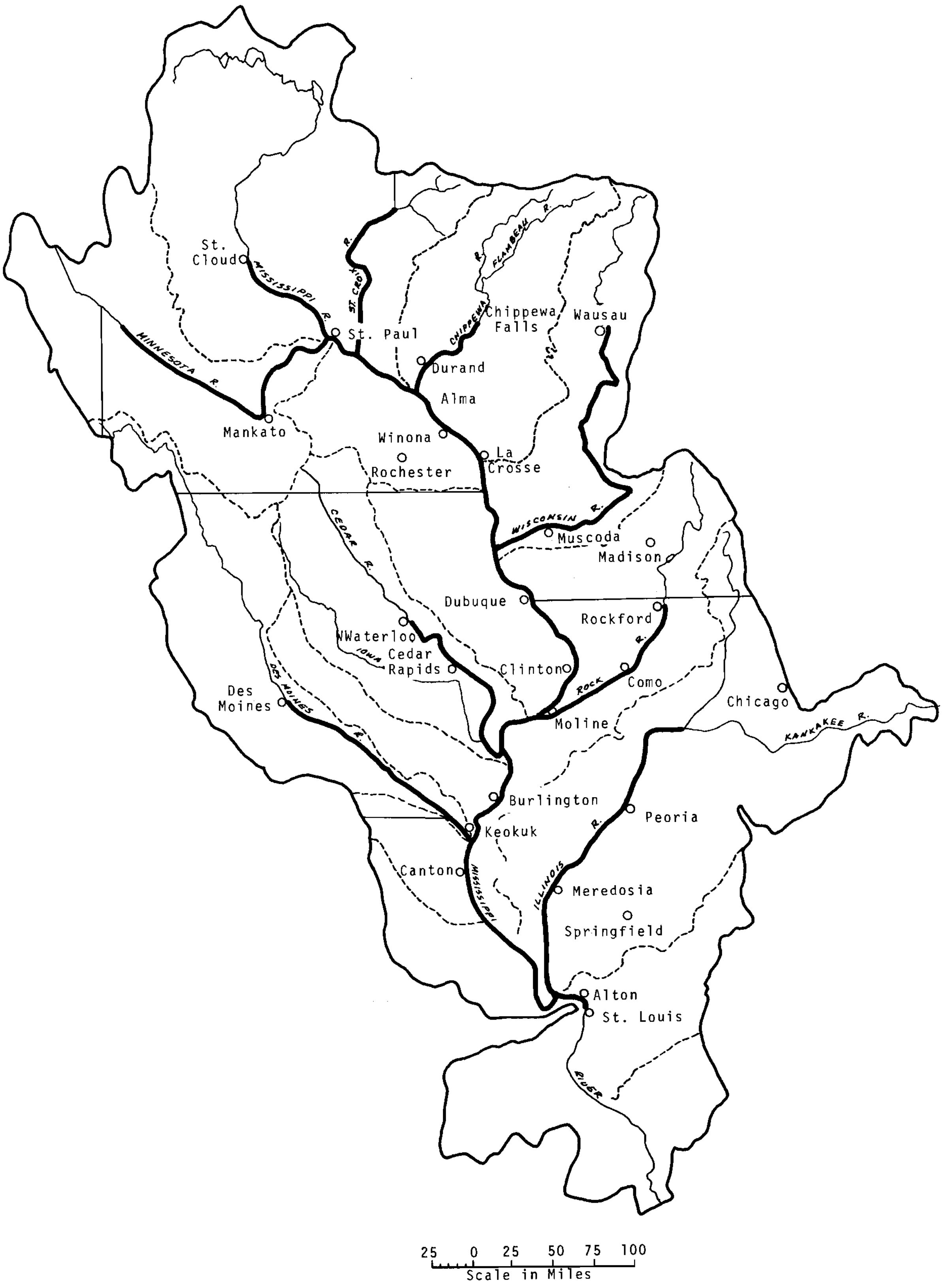


FIGURE 1. *Upper Mississippi River Basin*

SUMMARY AND CONCLUSIONS

The principal objective of simulating the 1964 thermal regimen of the Upper Mississippi River and its major tributaries, by utilizing the COL HEAT river model and regional weather and flow data, was accomplished. The secondary objectives of simulating the potential effects of 1970, 1980 and year 2000 regional power forecasts were also carried out.

Specific conclusions resulting from the study are as follows:

- The study indicates the applicability of the COL HEAT river model to the simulation of regional power development systems. It illustrates the importance of advance planning on a regional basis to ascertain the relative potential effects of available options. As an example, the use of simulation systems, such as COL HEAT, offers an opportunity for both the conservationist and the developer to review questions of significance in the early stages of system development.
- State Water Quality Standards specify maximum stream temperatures along the Mississippi varying from 30°C in Minnesota to 32°C in Missouri. Under weather and flow conditions prevailing in 1964 (flow was 57 percent of normal for the basin as a whole), 1,000 MW nuclear steam plants using flow through cooling would, in general, require special provisions to remain within the indicated maximum temperatures during the mid-summer period. In general, the Standards also specify that effluents shall not change the average stream temperature by more than 2.8°C. The tendency to aggregate nuclear capacity

in super plants of very large rating aggravates the general problem of heat dissipation because of the limitations on the local temperature rise imposed by State Standards under the Water Quality Restoration Act of 1966. The data developed for individual sub-basins supplying the UMRB is especially useful in detailing the specific inter-dependence of plant size, load factor and stream capacity. These facts suggest that the optimization processes involved in plant size determination should include the entire system from water source to heat sink in the venture analysis supporting process selection. As a corollary, the study suggests the retention of a line of smaller, flexibly designed plants which could be used for regions which could incorporate direct cooling on smaller streams with appropriate electrical flexibility for low voltage regional systems.

- The comparison of attenuation or equilibration rate favors the use of the slowest moving portion of reservoirs or river reaches where the mixing zone does not reach temperatures which are prohibitively high. This suggests that the use of reservoirs or trapped embayments along the main stem of wide meandering streams such as the Mississippi offers a good way to increase heat sink capability of the stream without exceeding regulator limits for the mixed flow regimen. Retention of the discharge on the pond or lake surface as a stratified overflow induces the fastest cooling rate. However, since retention of stratification is difficult on streams with currents in excess of 0.2 knots, this approach is limited to special cases such as Peoria Lake on the Illinois

Waterway and similar situations.

- Inferentially from the prior two conclusions, the study suggests that the use of cooling ponds is a preferential alternative to cooling towers from the standpoint of minimizing consumptive use where such use is under allotment and regulation by International treaty or by interstate compact and requires consideration as part of the systems concept for the plant under consideration.
- The study permits the conclusion that by the year 2000, the available sites for use with direct cooling without some supplementary system will all be developed. Further, an examination of the specific data for individual reaches and tributaries of the main steam indicates that the figure of 35% assigned in previous Federal Power Commission forecasts for plants which would require supplementary systems or cooling towers may be too low.
- The study also indicates that many tributaries offer excellent opportunities for the use of direct cooling without significant modification of the historical temperature regimen beyond a short distance below the mixing zone.
- By the year 2000 it appears that thermal effluents could be an important factor in providing year-around navigation as far north as the Twin Cities.
- Open water on some reservoirs during the winter months (e.g., the Hastings Reservoir upstream of Lock and Dam No. 2) would probably result in an increase in dissolved oxygen relative to the immediate past. In general, ice and snow combined with the

Biochemical Oxygen Demand of water born organic materials has resulted in a low level of dissolved oxygen in the Hastings Pool.

OBJECTIVES

The objectives of the Upper Mississippi River Basin study included the following:

- Demonstration of the applicability of the COL HEAT computer program for the simulation of a large river system in which there are marked differences in the characteristics of some of the principal streams.
- Prediction of the downstream effects of specific nuclear generating plants scheduled for operation in 1970, with direct cooling assumed.
- Prediction of the effects of projected nuclear power requirements for the year 1980.
- Prediction of the effects of projected nuclear power requirements for the year 2000.

SIMULATION MODEL

The COL HEAT simulation model has been described in previous reports and publications,(4) and has been extensively used both on the Columbia River and other tributary systems for the operational analysis of the effects of industrial development.(1) The computational system operates on the assumption that most streams will be turbulent or supercritical in hydraulic characteristics and that, within this assumption, the distribution of velocity within the stream is similar regardless of the stream dimensions. Based on this concept, the model sets up a series of **difference equations** derived from the heat budget method and iteratively computes the downstream temperatures as a function of the input parameters in the following manner:

$$T_{i+1,j+1} = (1-B)\left(T_{i,j} + \Delta T^{(1)}_{i,j} + \Delta T^{(2)}_{i,j}\right) + B\left(T_{i,j-1} + \Delta T^{(1)}_{i,j-1} + \Delta T^{(2)}_{i,j}\right)$$

where $T_{i,o}$ = average temperature of water entering the system during the i th time interval, °C.

$T_{i,j}$ = average water temperature of the beginning of the j th flow increment at the end of the i th time increment (flow day) °C

$\Delta T^{(1)}_{i,j}$ = the temperature change during the first half of the i th time interval in the j th flow increment as determined from surface heat exchange plus advected energy (heat budget) in °C

$\Delta T^{(2)}_{i,j}$ = same as above except for the second half of the i th time interval, in °C

B = the fractional part of the water in the inner fast moving trough.

A flow day of water is approximately the mean daily flow of all the water in the system.

In the simulation model the water system is composed of an inner and outer trough with relative volumes B and (1-B), respectively (see Figure 2). If A is the number of mean flow days, then the number of outer trough flow days is the largest integer, NJ, in

$$(1 + B) \cdot \Delta + 0.5 \; .$$

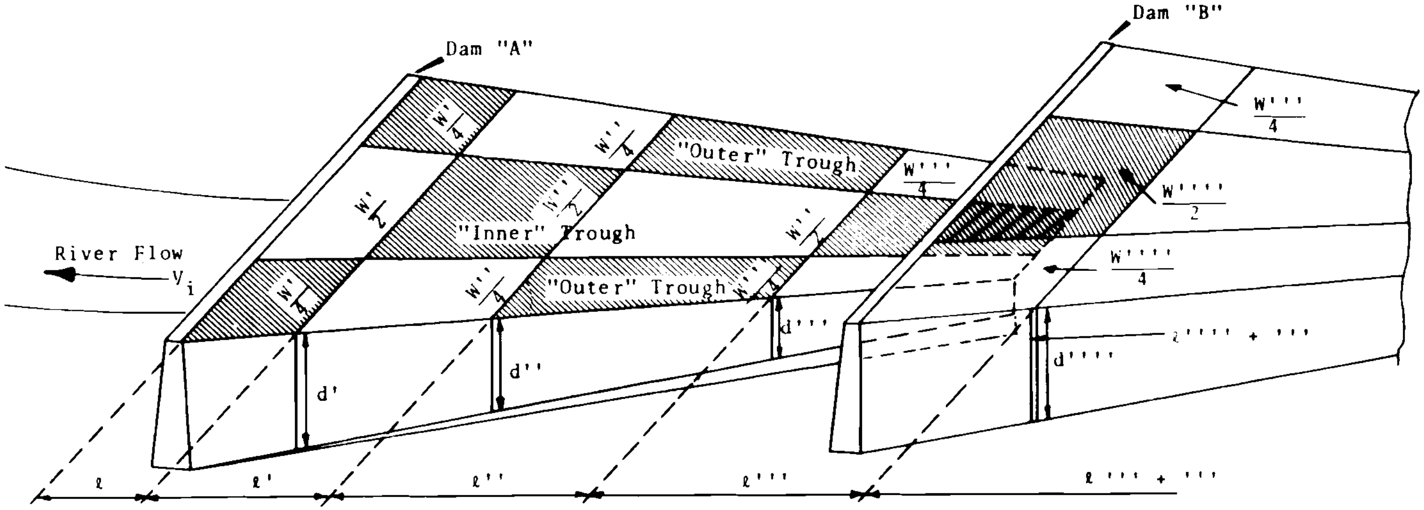
The system is then divided into NJ equal volume nodes which are also referred to as flow days or flow volumes.

Note that the above definitions have analogous meanings for time increments other than a day; for example, flow-hour.

The following data are required for operation of the temperature model:

- Water temperature at the inlet end (time increment appropriate)
  Flow discharge at the outlet end
- Water temperature at the outlet end (optional, for statistical comparison where available)
- Meteorological data (wind velocity for time period, mean air temperature, dew point, sky cover in tenths, short wave radiation)
- River or reservoir dimensions reduced to equivalent non-parallel trapezoidal cross sections (volume, surface or bottom areas are derived)
- Advected heat quantities (megawatts per time incrementation)

The model permits the advection of heat into any of the input defined troughs. The flow day(s) of water corresponding to the advected heat trough are adjusted in temperature to simulate the addition of the heat. A more detailed description of the simulation system is available in References (4,5,6).



1. ℓ varies as reservoir geometry and flow and represents a reservoir length for that region one flow day in length
2. $W = 2\left(\frac{W}{4}\right) + \frac{W}{2}$ when B the volume fraction of the center trough = 0.5

FIGURE 2. Representation of Model of Channel Flow at a Translational Instant

The foregoing data requirements provide a topical outline for the following discussion.

Water Temperatures

Temperature records for input data at the upstream terminus of the model and for comparative information at downstream points in the system were obtained from: U. S. Geological Survey/Water Resources Division, City of Minneapolis/Fridley Filtration Plant, State of Minnesota/Pollution Control Agency, Dairyland Power Cooperative, State of Wisconsin/Department of Natural Resources, City of Moline/Water Department, City of Quincy/Water Works Commission, Alton Water Company.

Input records are not required for the proper functioning of the COL HEAT model; they are used primarily to facilitate convergence of the finite difference equations, which comprise the model. Consequently, the degree of accuracy of these data was not of overriding importance. Downstream records were utilized as indicators of the general validity of the simulation.

Flow Records

Daily average flow records for the Mississippi River were obtained from U. S. Army, Corps of Engineers records, which were generally available in unpublished form for most of the locks and dams of the Upper Mississippi Waterway, and from Water Supply publications of the U. S. Geological Survey. Flow records for all tributary streams were obtained from U. S. Geological Survey publications. Wide diurnal fluctuations in flow induced by the operation of control structures would be significant to the travel time analysis of a transient pulse of heat. However, artificial heat was added to the model in a steady state or cyclic form that did not appear to be seriously affected by diurnal variations in flow. This is consistent with the regional interpretation of the cases rather than examination of local detail. The model can be utilized to define transient events when desired; however, the field data requirements are much more exacting than they are for a reconnaissance study.

Meteorological Data

The input data required for operation of the simulation system include the five major variables involved in the heat budget computation. Of these, the input radiation and the dry bulb temperature are the strongest, the others less strong in the order of dew point, wind speed, and finally, cloud cover. The latter is involved only in the estimate of the long wave radiation exchange, since measured values of the short wave input radiation are used. The information was acquired from the National Weather Records Center at Asheville, North Carolina. Radiation data from 6 stations were utilized in the study, including: St. Cloud, Minnesota; Ames, Iowa; Madison, Wisconsin; Lemont, Illinois; and Columbia, Missouri. Weather data from several stations were also used in the simulation of Mississippi River temperatures: St. Cloud, St. Paul, LaCrosse, Dubuque, Moline, Burlington, Columbia and St. Louis (see Figure 1). A similar pattern of stations spaced from 50 to 100 miles apart was used for the simulations of the tributary streams. The apparent successful utilization of regional weather and radiation data for reconnaissance river temperature simulations has been an important economic factor in this and related studies. A field program to obtain more detailed information in a region as large as the Upper Mississippi Basin appears unnecessary and would be exceedingly costly.

Stream Parameters

River cross-section charts and flow profiles for the Mississippi River between St. Paul and Alton, Illinois were obtained from the U. S. Army, Corps of Engineers. These data were reduced to equivalent trapezoidal sections in which the surface area and total volume were conserved, the water depth was taken as the average depth and the bottom width was calculated. Any changes in the river due to scour and fill after the soundings were taken were assumed to be balanced, so that the net change in the system would be negligible. Between Minneapolis and St. Cloud, Minnesota, on the Mississippi, and in several reaches of the various tributary streams, cross-sections data were not available. In those reaches the surface area was obtained from topographic maps and the other parameters were estimated by utilizing flow and travel time information.

Advected Heat

Energy production in the Upper Mississippi Power Region, which will require condenser cooling, has been estimated at 130 x 10^9 kWh for 1970, 270 x 10^9 kWh for 1980 and 770 x 10^9 kWh in the year 2000, according to the most recent projections of the Federal Power Commission.(22) The projections were further divided into (8) subarea forecasts. Table 1 indicates the Composition of Thermal-Electric Power Supply Requiring Condenser Cooling through the year 2000. In 1980 77 percent, and in the year 2000 67 percent, of the total is expected to require flow

TABLE 1

Composition of the Thermal-Electric Power Supply Requiring Condenser Cooling in the Upper Mississippi River Basin Power Region(22)

	Nuclear			Coal		
PSA	Energy Produced Million kWh	CF	Capacity MW	Energy Produced Million kWh	CF	Capacity MW
			1960			
12	-	-	-	3,175	-	625
13	-	-	-	2,458	.41	680
14	254	.14	209	23,814	.48	5,690
15	-	-	-	7,287	.53	1,576
16	-	-	-	7,968	.47	1,922
17	-	-	-	6,341	.45	1,589
26	-	-	-	23	.26	10
40	-	-	-	7,268	.42	1,988
Total	254	.14	209	58,334	.47	14,080
			1980			
12	7,378	.80	1,050	6,912	.55	1,730
13	7,027	.80	1,000	10,092	.47	2,463
14	65,653	.68	11,000	24,025	.30	9,117
15	5,621	.80	800	31,933	.47	7,702
16	21,081	.80	3,000	13,992	.43	3,689
17	14,054	.80	2,000	16,478	.43	4,332
26	-	-	-	628	.48	149
40	-	-	-	43,514	.56	8,768
Total	120,814	.73	18,850	147,574	.44	37,950
			2000			
12	41,080	.74	6,350	730	.05	1,640
13	47,082	.80	6,700	1,973	.08	2,666
14	265,039	.57	52,800	-	-	5,314
15	81,130	.73	12,700	31,110	.25	14,352
16	114,441	.72	18,100	1,380	.04	4,409
17	80,110	.80	11,400	16,225	.25	7,354
26	-	-	-	1,938	.49	449
40	59,012	.80	8,400	229,583	.28	11,818
Total	687,894	.67	116,450	82,939	.20	48,002

PSA - Power Subarea
kWh - Kilowatt Hours

CF - Capacity Factor
MW - Megawatts

through cooling. However, in transforming these requirements into estimates of waste heat advected into the environment flow through cooling was assumed for all plants in the region. This was done in order to ascertain the maximum impact upon the system and thus single out sectors on the various streams where other forms of cooling may be advantageous. It was also assumed that the mean capacity factor (i.e., the ratio of the average load to the plant capacity) for each power subarea would apply to each power plant within the subarea, and that all nuclear power plants would have a thermal efficiency of 32% in 1970 and 40% in the years 1980 and 2000. Fossil fuel plants were assumed to have an efficiency of 40%.

Table 2 indicates Scheduled and Installed Nuclear Capacity in the UMRB Power Region. Four nuclear power plants, with a total capacity of 1,269 megawatts, are scheduled to be in operation along the Mississippi River on or before 1970. The potential effects of these plants, within the given assumptions, were readily simulated. Table 3 indicates the location and assumed capacity of fossil and nuclear steam plants used in the 1980 and 2000 simulations. For the years 1980 and 2000, there was uncertainty as to the specific locations and capacity of individual power plants in each power subarea. Therefore, there was a degree of arbitrariness in the location and capacity of plants in the 1980 simulation and a greater degree in the year 2000 simulation. In general, the hypothetical plants for 1980 and 2000 were situated near sites of fossil fuel plants currently in existence. There is no experience that would suggest that the sites selected are optimal, or even practical. The 1980 simulation includes 100 percent of projected capacity

TABLE 2

Scheduled and Installed Nuclear Capacity in the UMRB Power Region (22)

PSA	Plant or Location	Utility	Capacity (MW)	Scheduled Operation
13	Genoa (Miss. R.)	Dairyland Power Cooperative	50	1967
14	Dresden #1 (Ill. R.)	Commonwealth Edison Company	200	1960
	Dresden #2	Commonwealth Edison Company	715	1969
	Dresden #3	Commonwealth Edison Company	715	1970
	Zion #1 (L. Mich.)	Commonwealth Edison Company	1100	1972
	Zion #2	Commonwealth Edison Company	1100	1973
16	Elk River (Miss. R.)	Rural Coop. Power Association	22	1963
16	Monticello(Miss. R.)	Northern States Power Co.	472	1970
16	Prairie Island #1 (Miss. R.)	Northern States Power Co.	550	1974
	Prairie Island #2 (Miss. R.)	Northern States Power Co.	550	1974
17	Quad Cities #1 (Miss. R.)	Commonwealth Edison Company	715	1970
	Quad Cities #2	Iowa-Illinois Gas & Elec. Co.	715	1971
17	Cedar Rapids #1 (Cedar River)	Iowa Electric Light & Power Co.	550	1973
	Cedar Rapids #2	Iowa Electric Light & Power Co.	550	?
17	Iowa Station (Des Moines R.)	Iowa Utilities	550-750	1975

TABLE 3

Hypothetical Steam Generating Plants Utilizing Flow Through Condenser Cooling

	1980		2000	
Mississippi River Mile	Capacity	Capacity Factor	Capacity	Capacity Factor
926	75	43%	1,000 (n)	72%
900	500 (n)	80%	1,500 (n)	72%
878	22 (n)			
853	550	43%	2,000 (n)	72%
852	75	43%		
844	75	43%		
839	500	43%	2,500 (n)	72%
800	1,100 (n)	80%	2,100 (n)	72%
791	75	43%	1,000 (n)	72%
770			1,000 (n)	72%
747	225	43%	1,000 (n)	72%
726	100	43%	1,000 (n)	72%
697	100	43%	1,000 (n)	72%
679	500 (n)	80%	1,000 (n)	80%
658			1,000 (n)	80%
632			1,000 (n)	80%
605	500	47%	1,000 (n)	80%
580	500	43%	2,000 (n)	80%
545			1,000 (n)	80%
512	1,430 (n)	80%	2,000 (n)	80%
489			2,000 (n)	80%
456			1,000 (n)	80%
428			1,000 (n)	80%
400			1,000 (n)	80%
375			1,000 (n)	73%
350			1,000 (n)	73%
322			1,000 (n)	73%
293			1,000 (n)	73%
265			1,000 (n)	73%
240	500 (n)	80%	2,000 (n)	73%
215	500	80%	2,000 (n)	73%
211	800	47%		

in PSA 13, 38 percent in combined PSA 14 and 40 capacity, 125 percent in PSA 15, 61 percent in PSA 16 and 125 percent in PSA 17. In the year 2000 simulatiion the capacity utilized in the model is 92 percent of the amount projected by the Federal Power Commission for PSA 13, 32 percent for PSA 14 and 40 combined, 71 percent for PSA 15, 86 percent for PSA 16 and 98 percent for PSA 17.

SIMULATIONS

Because of the general availability of basic data, including river flows, river temperatures, short wave (solar) radiation and weather, the year 1964 was selected for simulation purposes in this study. It should be noted that the quantities of advected heat wasted to the streams in the 1970, 1980 and 2000 simulations were imposed upon the 1964 flow regimen and, consequently, are not indicative of average conditions. On an annual basis, 1964 was a low flow year with an average flow for the Upper Mississippi River Basin of 57 percent of the long term mean.(16) However, because of the interrelationship of flow and weather, further study would be required before a statement could be made concerning the relative annual capacity of the streams to dissipate waste heat. No attempt was made in this study to simulate a mean response or to define an envelope of extreme conditions.

Minnesota River

The Minnesota River, which joins the Mississippi at Minneapolis (see Figures 1,3), is the first downstream tirbutary to be simulated in this study. The stream traverses an area of southern Minnesota, which is largely devoted to agriculture. An exception to this is the Twin City

Metropolitan area near the mouth of the river. In terms of rainfall, the Minnesota River Basin is the driest of the tributary Basins covered by this study. The annual average precipitation varies from 20 inches in its upper reaches to 28 inches near the Twin Cities.(19) The mean discharge of 3,148 cubic feet per second (cfs) is likewise the lowest of the study. It is a major stream, however, with a flow approximately 1/2 that of the Mississippi before the confluence with the Minnesota. River cross-sections were available for the entire course of the river from Ortonville (RM 329) to Minneapolis. As a result there was better definition of local variations in dimensions of this stream than in any other tributary, with the exception of the Illinois Waterway. Flow data were available from gaging stations at Ortonville (RM 329), Odessa (RM 319), Montevideo (RM 271), Mankato (RM 106) and Carver (RM 36).(13,14)

Model Verification

Observed water temperatures for 1964 were secured from the Minnesota Pollution Control Agency at three locations along the Minnesota River. The data for a station located at Bloomington (RM 7.4) are shown in Figure 4, along with the simulated temperatures; the simulated temperatures appear to be in good agreement with observed data. No modifications of the model to include the effects of groundwater were deemed necessary in this simulation. The sediments (glacial till) in much of the Minnesota River Basin are generally very fine grained and have a low permeability. Consequently, even though permeable alluvium is extensive in the lower reaches of the main valley, recharge from groundwater would be limited. Another potential modifier of the outlet temperature of the river is the Black Dog Steam Plant of the Northern

States Power Company, which is located near the Bloomington temperature sampling station. However, the Black Dog Plant has used a cooling pond to cool condenser effluents during periods of low flow.(22)

Projected Conditions

No change of significance with respect to power output and condenser cooling requirements was anticipated for the Minnesota Valley between 1964 and 1970. In 1980 an average increase over 1964 of 50 MW in capacity was assumed for each of five steam (fossil fuel) plants situated on the river. The average annual increase in river temperatures (at the mouth of the Minnesota) due to the increased load was calculated to be 0.15°C. Power requirements in PSA 16 (which includes the Minnesota, the Mississippi downstream to RM 668, the St. Croix and Chippewa Rivers) are expected to increase from 35 BkWh (Billion Kilowatt-hours) in 1980 to 116 BkWh in the year 2000. Fossil-fueled steam plants are expected to have been largely phased out of production by the turn of the century (in PSA 16), so that 114 BkWh of the total demand would be supplied by nuclear generation. A nuclear capacity of 18,100 MW is expected to supply the required power.(22) Of this total, three plants, with a capacity of 500 MW each, were hypothetically located on the Minnesota River: at Mankato (RM 122), Belle Plaine (RM 50), and Bloomington (RM 9); the Bloomington site also would receive heat from other sources. The annual average effect of these plants is illustrated in Figure 5. A residual effect of 4.6°C was calculated at the outlet; this, however, results primarily from the proximity of the hypothetical plant at River Mile 9. The residual effect at Mile zero of the two upstream plants would be less than 1°C.

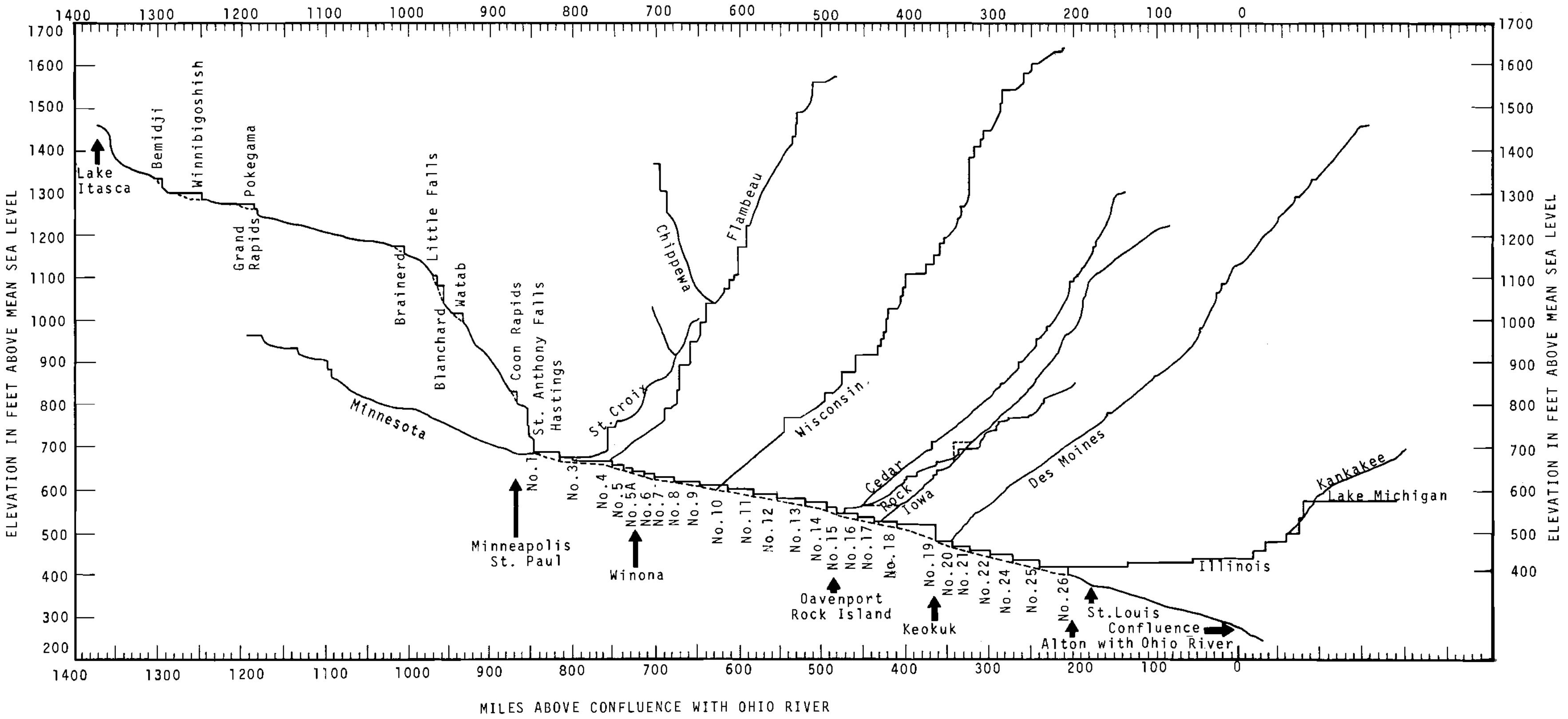


FIGURE 3. *Upper Mississippi River, River Profiles Main Stem and Major Tributaries*

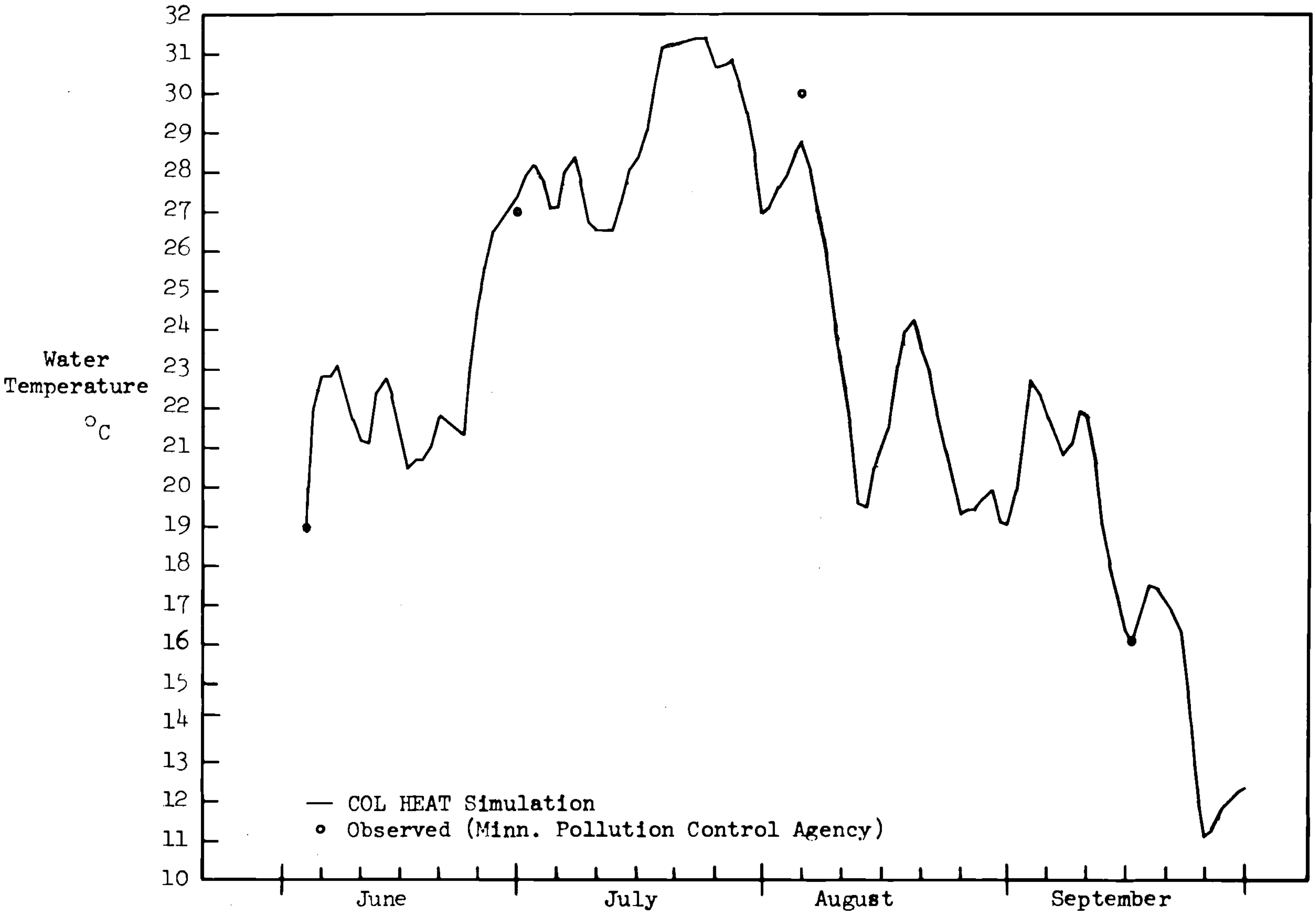


FIGURE 4. *Minnesota River at Bloomington-Comparison of 1964 Measured and Computed Temperatures*

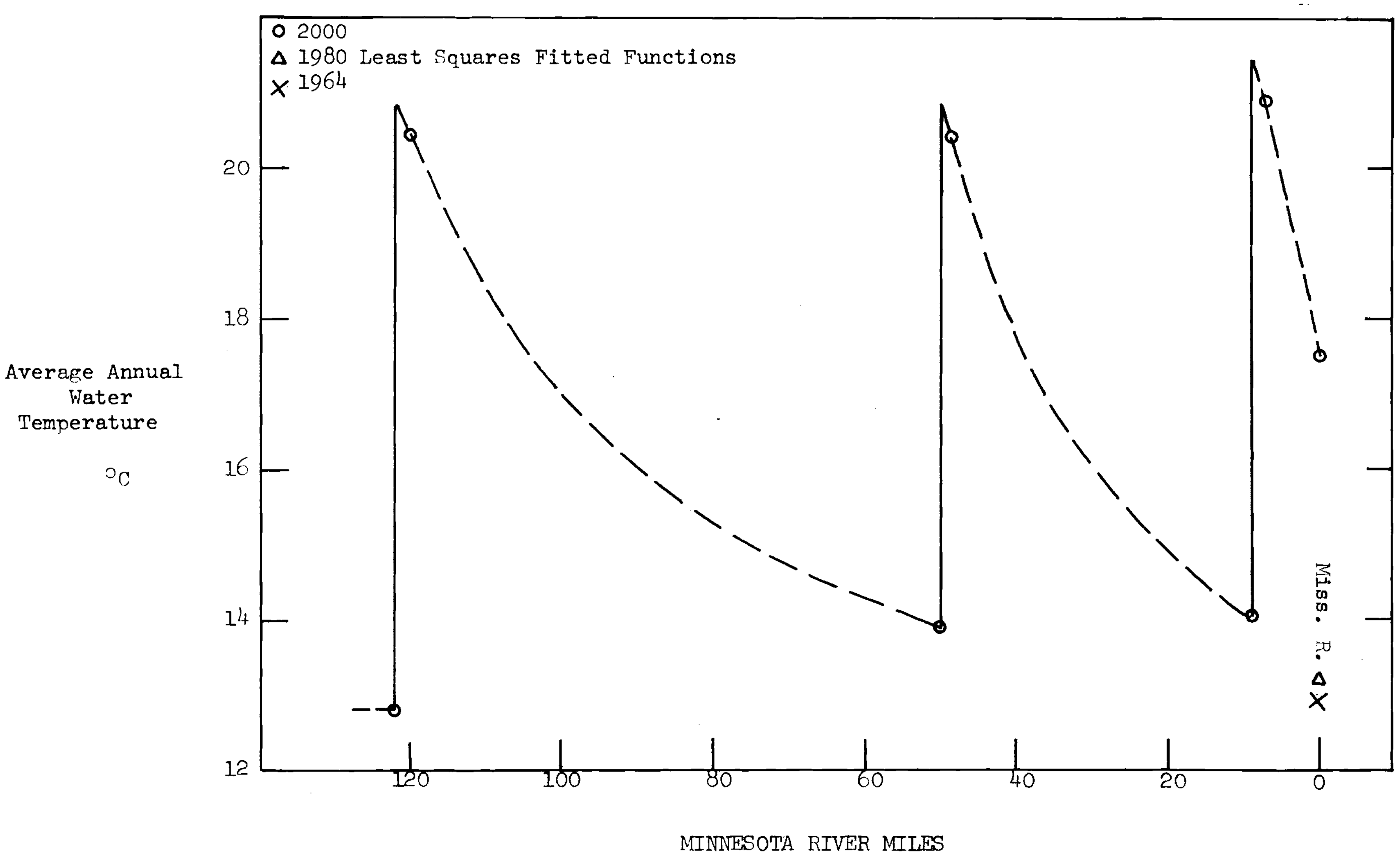


FIGURE 5. Equilibration Profile, Minnesota River

The State of Minnesota Pollution Control Criteria for the Minnesota River place a temperature limit of 30°C (68°F) upstream of Carver Rapids (RM 36).(26) An observed temperature of 25°C was recorded at Courtland (RM 129) on July 6, 1964, by the Minnesota Pollution Control Agency. Temperatures near or slightly above 30 C were calculated for the Courtland-Mankato area during the latter two weeks of July 1964. Consequently, the increase in river temperatures due to a hypothetical plant in this area would result in temperatures 3° to 10°C in excess of the limit near the plant outfall during the month of July. Analysis of data for the hypothetical Belle Plaine plant indicates that a similar 3° to 10°C effect would be noted downstream to Carver Rapids. From a generalized viewpoint the foregoing statements are restricted by the 1964 weather and flow conditions and the hypothetical nature of the power plants. They do indicate, however, that for nuclear units of 500 MW or greater capacity, some special requirement would be necessary in the reaches above Carver Rapids.

St. Croix River

The St. Croix River has a unique status among the rivers of this study in that it has been included under "Wild Rivers" legislation presently before the U. S. Congress. As would be expected of any stream with a "Wild River" designation, there is only minor agricultural and urban development in its basin. This is especially true upstream of St. Croix Falls (RM 52), where wood products and recreation are the major industries. Cross-section data were available for modeling purposes to river mile 52. From St. Croix Falls to the Danbury gaging station (RM 129) cross-sections were not available; thus, it was necessary to estimate the sections in the upper half of the study area. No simulations were made upstream of the Danbury gaging station. Daily flow data were obtained for gaging stations at Danbury, Grantsburg and St. Croix Falls from U. S. Geological Survey Publications.(13,14) The mean annual flow at St. Croix Falls is 4,030 cfs. The mean flow for the 1964 calendar year was 3,383 cfs, 84 percent of normal.

Model Verification

Temperature data for the St. Croix River were available from the Minnesota Pollution Control Agency for stations at Danbury (RM 111), Osceola (RM 45) and Prescott (RM 0). Data were also secured for the Prescott location from the Wisconsin Department of Natural Resources.(7) Figure 6 illustrates computed 1964 water temperatures compared with observed data for the Prescott station. The simulation required no modification of the model to accommodate factors such as shading of the water surface and/or the modifying effects of groundwater. This is interpreted as indicating that the St. Croix is essentially in equilibrium with daily average atmospheric conditions by the time the water reaches the confluence with the Mississippi. Because of the presence of large springs in the St. Croix Falls-Osceola area, groundwater was expected to exert a significant influence on the outlet temperature of the St. Croix River; however, the influence, even though it undoubtedly exists, appears to be minor.

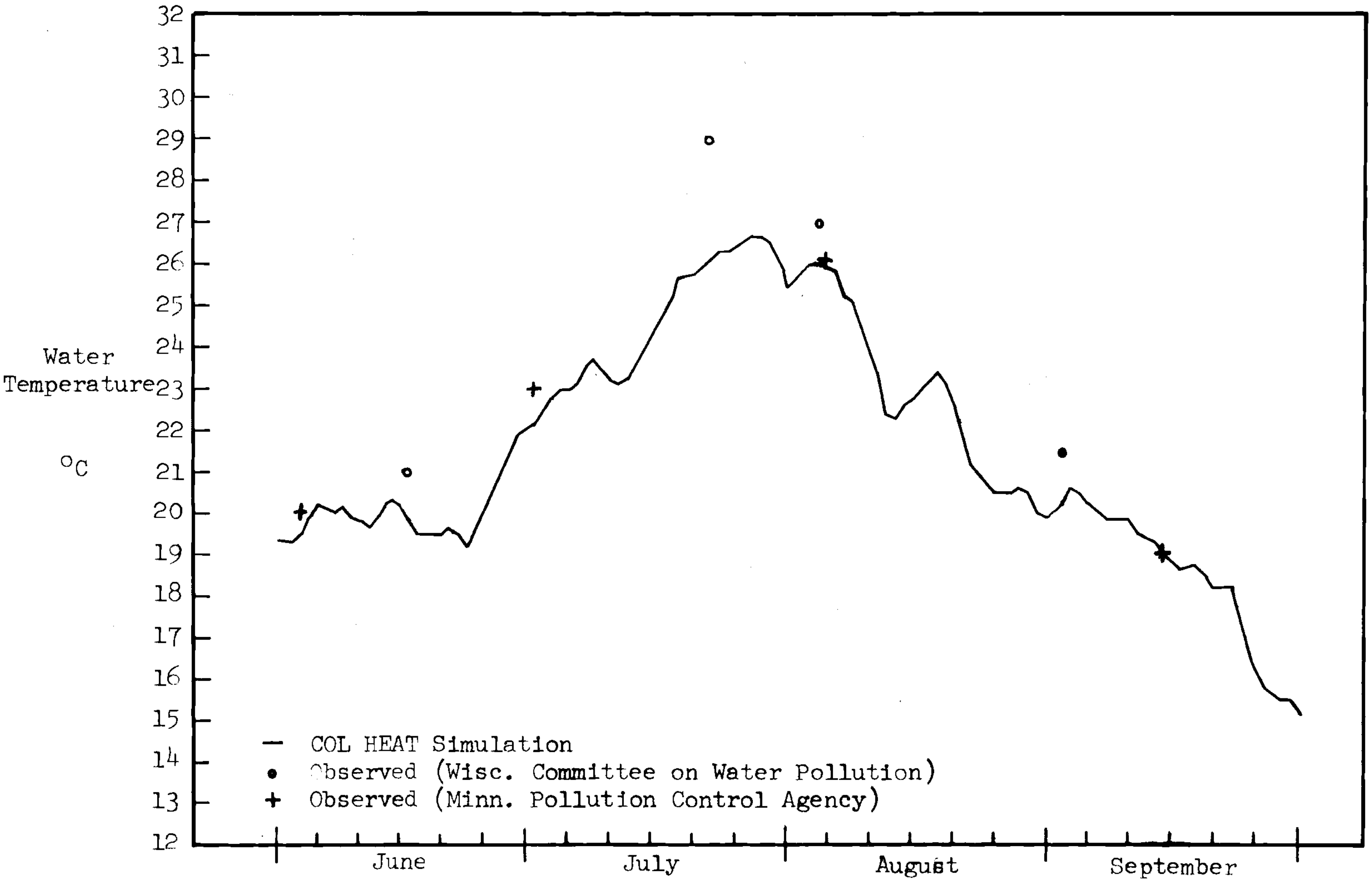
Projected Conditions

At the present time the Northern States Power Company is constructing a steam generating plant (fossil fuel) near Bayport, Minnesota

(RM 6) on Lake St. Croix.(23) Because the plant reportedly will operate in conjunction with a cooling tower no heat was added to the model at that location. Because of the possible "Wild River" status of the St. Croix no additional power plants were projected for its basin through the year 2000. Consequently, the water which was mixed with Mississippi River water in the 1980 and 2000 simulations has a cooling effect upon the Mississippi.

One 1,000 MW steam generating plant (Efficiency, 40 percent; Capacity Factor, 72 percent) was arbitrarily located at River Mile 52 in order to ascertain its effect on the lower reaches of the St. Croix; the results of that simulation were not mixed with Mississippi flows. Figure 7 shows the calculated average annual change in water temperatures in the lowermost 50 miles of the St. Croix, which would result from the operation of the hypothetical 1,000 MW plant. The average annual residual effect of this plant was calculated to be less than 0.2°C at the mouth of the river. The effect near the plant outfall was calculated to average approximately 3°C above 1964 stream temperatures.

The State of Wisconsin Water Quality Standards indicate a 2.8°C (5°F) permissible change from natural background and a 28.8°C (84°F) maximum temperature for the St. Croix River.(29) The July 1964 maximum calculated for the plant site was 26.8°C, without heat from the hypothetical plant. The effect near the plant outfall on the same date was calculated to be 7°C above background. As indicated previously, the calculated temperatures do not presage expected conditions. The hypothetical case does indicate, however, that a 1,000 MW plant in the vicinity of RM 50 would need some form of special requirement to avoid exceeding the maximum



<u>*FIGURE 6*</u>. *St. Croix River at Prescott-Comparison of 1964 Measured and Computed Temperatures*

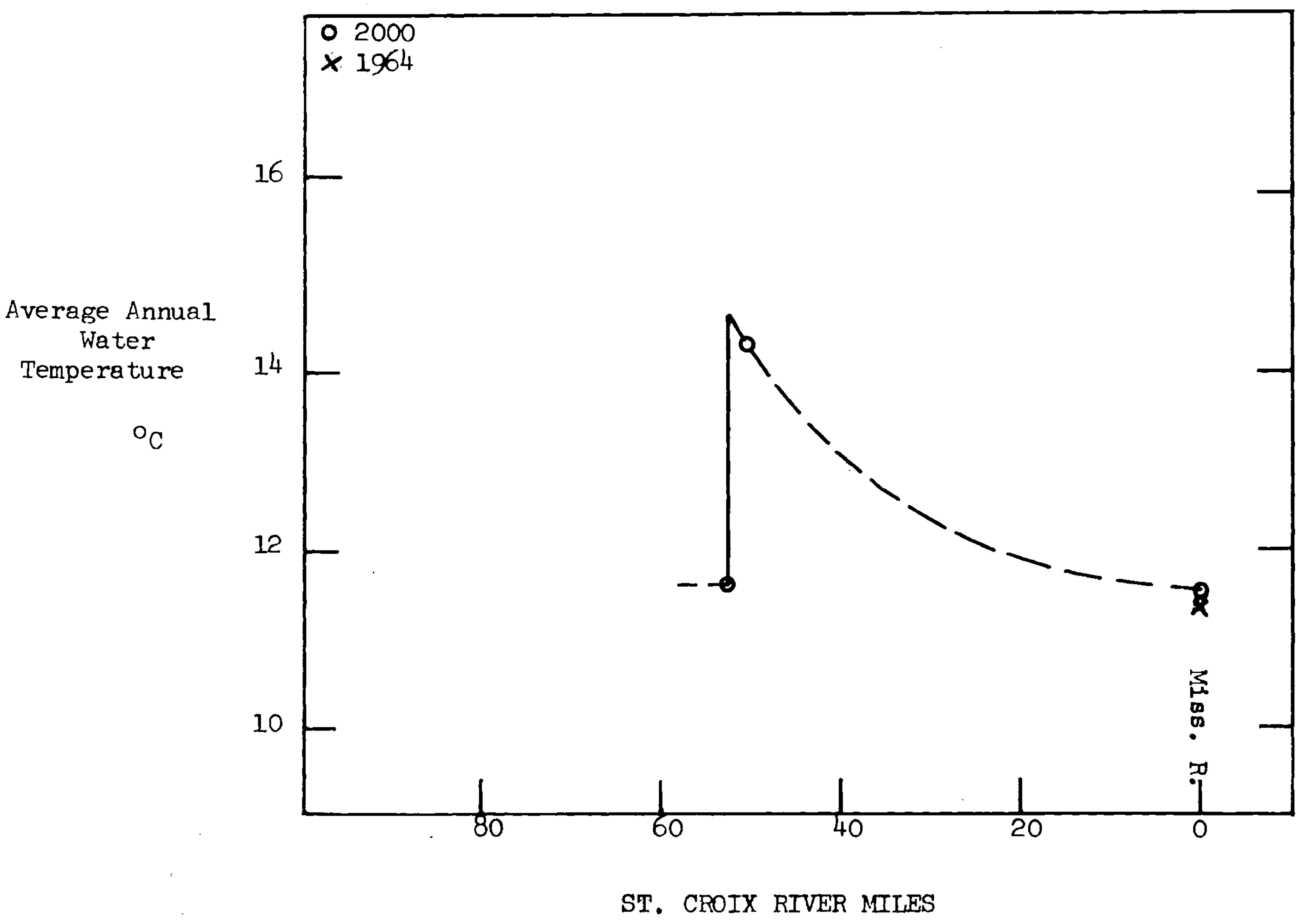


FIGURE 7. Equilibration Profile, St. Croix River

during the summer months. The calculated average annual residual effect of 3°C above background for 1964 conditions is so close to the 2.8°C limit that it appears that a special requirement would also be necessary under certain conditions.

Chippewa River

The Chippewa River is one of the most important hydropower producers in the Upper Mississippi River Basin. In 1966 the installed hydroelectric capacity in its watershed was 162 MW.(22) Thermal generation is presently nonexistent; however, there is some industrial use of direct cooling in the Eau Claire area. The mean annual flow of the Chippewa River near Durand (RM 18) is 7,206 cfs; the 1964 average was 4,751 cfs, 66 percent of normal.(17,18) Average monthly discharges range between 4,200 cfs and 14,500 cfs.(20) Cross-section data were generally unavailable for the Chippewa River, with the exception of a 7 mile reach near the mouth of the river. Consequently, the river sections were estimated from topographic maps and flow data.

Model Verification

Temperature data for 1964 were limited to 2 stations on the Chippewa River, one at Chippewa Falls (RM 75) and the other near Pepin (RM 2).(7) Because of this limitation, the section of the river selected for simulation was between Lake Wissota (RM 78) and the mouth of the river at Lake Pepin. Figure 8 illustrates the results of the simulation in comparison with observed temperatures. Downstream of Chippewa Falls the water levels of the Chippewa River and its tributary stream lie below the groundwater table. Because of the sandy soils in the area, seepage of groundwater into the streams can be appreciable. Springs in the area have a water temperature range between 5°C (winter) and 10°C (summer). In order to accommodate groundwater into the simulation, inflow that could not be accounted for by stream flow was assumed to result from seepage with an annual temperature cycle between 5°C and 10°C. The results, which appear satisfactory for reconnaissance purposes, are shown in Figure 8. It should be noted that a satisfactory fit does not prove in a mathematical sense that a simulation is unique. The simulation is considered satisfactory because a fit to observed data was achieved after inclusion of a feature (groundwater), which field evidence indicates is more important in the Chippewa Basin than in most other tributary Basins of this study.

Projected Conditions

As indicated previously there are presently no thermal power plants in the Chippewa Basin. By 1980 the demand for power in subarea 16 of the FPC will have increased to the point where thermal generation along the Chippewa River may be required. Consequently, one plant, with a capacity of 300 MW, was sited along the Chippewa River (RM 75) in the 1980 simulation. The effect of the hypothetical plant was an increase of 0.1°C in the (1964) average annual temperature at the mouth of the river. In the year 2000 nuclear generating capacity in PSA 16 is projected to have increased by a factor of six compared with 1980, an increase of 15,100 MW.(22) Of this increase, 1,700 MW are assumed to be generated along the Chippewa River. A 700 MW increase, for a total capacity of 1,000 MW, is assumed at Chippewa Falls (RM 75) and a 1,000 MW unit is assumed at Durand (RM 18). These two sites were selected where flow gaging stations presently exist; they are arbitrary and are not necessarily optimum locations. Figure 9 illustrates the average annual effect of these hypothetical power plants on the 1964 thermal regimen of the Chippewa River. The residual effect of these plants at Mile zero would be 1.2°C. The average increase in river temperatures below the outfall of the hypothetical plants is 5.2°C at Chippewa Falls and 3.2°C at Durand. The difference is largely a function of the fact that the flow of the river increased from an annual average of 3,154 cfs at Chippewa Falls to 4,751 cfs at Durand. Approximately 350 cfs of the flow was contributed by the Eau Claire River (RM 62) and 870 cfs by the Red Cedar River (RM 29). The dashed curve in Figure 9 can be expected to exhibit inflections in slope at each of these two points (i.e., RM 62 and 29); the nature of the slope was not defined in the study because computer readouts were taken only at Chippewa Falls, Durand and Lake Pepin.

The Wisconsin Water Quality Standards specify a 32°C (89°F) maximum and a 2.8°C (5°F) change from background for the Chippewa River.(30) Under the flow and weather conditions prevailing in 1964 the 32°C maximum would be exceeded due to flow through cooling of the hypothetical plant at Chippewa Falls once in late June, 15 times in July and 5 times in early August. The 2.8°C limit would be exceeded by an annual average of 2.4°C near the outfall. The only significant intervals in which the change would be less than 2.8°C would be a continuous 50 day period during the high flow months of April and May and a 5 day interval in mid-March. At Durand temperatures would be marginal with respect to the 32°C maximum during late July of the 1964 regimen; the 2.8°C standard would be exceeded frequently near the plant outfall during the summer months but only occasionally during the remainder of the year.

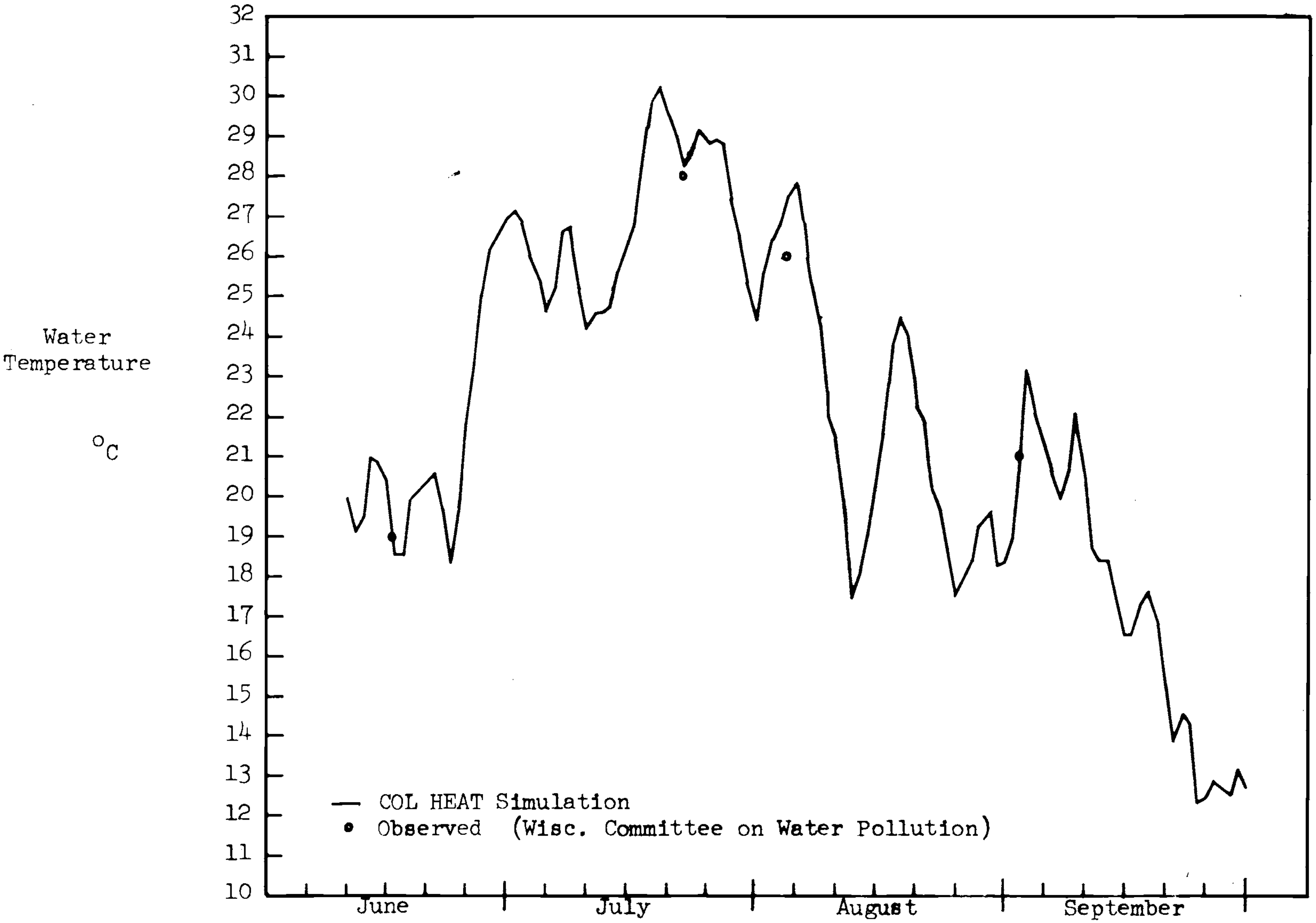


FIGURE 8. Chippewa River at Pepin-Comparison of 1964 Measured and Computed Temperatures

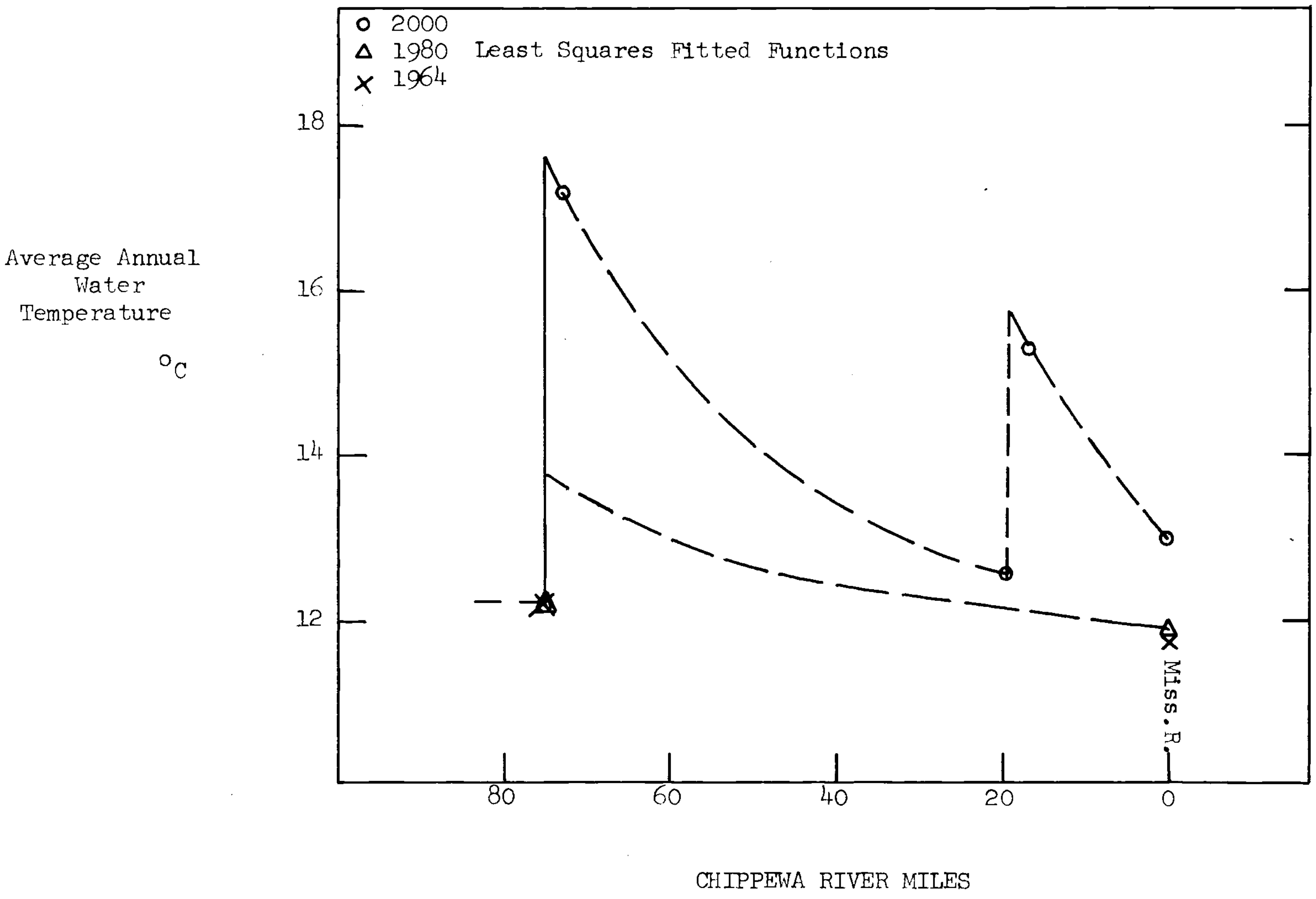


FIGURE 9. *Equilibration Profile, Chippewa River*

Wisconsin River

The upper reaches of the Wisconsin, like those of the Mississippi, St. Croix and Chippewa Rivers, lie in a forested region where wood products and recreation are major industries. The 260 mile lower section, which was simulated in this study, passes through an area of mixed farmlands, marshlands and woodlands. The Wisconsin River ranks behind only the Upper Mississippi and Chippewa Rivers in terms of installed hydroelectric capacity.(22) Its average annual hydroelectric energy production is second only to the Upper Mississippi. In contrast, only four fossil fueled steam generating plants, with a capacity of 166 MW, were in operation in 1964 along the Wisconsin. Over 80 percent of the steam generated energy was produced in the Wausau area.

The mean annual flow of the Wisconsin River is 8,423 cfs at the Muscoda gaging station (RM 39); the 1964 average was 5,148 cfs, 61 percent of normal.(17,18) This flow is second only to that of the Illinois River among tributary streams of the Upper Mississippi. Daily average flow data were available from U. S. Geological Survey publications for gaging stations at: Rothschild (RM 258), Wisconsin Rapids (RM 212), Wisconsin Dells (RM 132), Prairie du Sac (RM 90) and Muscoda (RM 39). Cross-section information was available only in the vicinity of Lake Wisconsin (RM 86 to RM 106). Consequently, maps and flow data were used to estimate cross-sections over the greater part of the stream.

Model Verification

Stream temperatures (approximately one per month) were available at Wausau, for input data to the model, and at Bridgeport (RM 7), for verification of the model.(7) Figure 10 illustrates calculated 1964 temperatures at Bridgeport compared with observed data. The Wisconsin River has a flow regimen similar to that of the Chippewa River in that its energy surface lies below the regional groundwater table, and in that the river valley contains a predominance of sandy outwash.(21) The outwash, largely glaciofluvial in origin, generally has a high permeability. This results in significant quantities of groundwater entering the river as seepage. The effect of this is that the Wisconsin River does not appear to approach equilibrium with daily average atmospheric conditions as closely as do most of the streams of this study. When groundwater was included, with a 5°C (winter) to a 10°C (summer) temperature range, the computed temperatures more closely fit the observed data. An exception was noted for August 13, when the calculated temperature was 24.9°C and the observed temperature 17.5°C. The reason for the discrepancy is uncertain. On August 11, winds increased and continued at a higher level through the 12th; air temperatures and dewpoint dipped approximately 5°C from the 12th through the 15th; solar radiation was low on the 12th; river flow was near the minimum for the year (2,350 cfs) on the 13th. All of these factors would tend to depress the water temperatures on the 13th. However, the fact that the observed temperature dripped to a much greater extent than did the calculated temperature may indicate that, under the combination of conditions prevailing on that date, groundwater exerted a significantly greater influence on river temperatures than was accounted for in the model. On August 11, at the onset of the unusual conditions, the observed temperature at Prairie du Sac (83 miles upstream) was 25°C compared with a calculated temperature of 26.2°C at Bridgeport.(7) In general, the observed temperatures at Bridgeport have been slightly warmer than those at Prairie du Sac; thus, the calculated value for the 11th appears in good agreement with the observed temperature.

Projected Conditions

No significant changes in thermal power production requiring condenser cooling are anticipated for the Wisconsin River Basin between 1964 and 1970. In the 1980 simulation one 500 MW nuclear steam plant is assumed at Rothschild. The site was selected because of a flow gaging station at that point and because of 1964 temperature input data collected at nearby Wausau. The effect of assumed flow through cooling of this plant would be an average annual change of 2.7°C near the outfall and an average annual 0.1°C residual 50 miles downstream. The residual effect was indistinguishable from background 90 miles downstream. Nuclear generating capacity in PSA 13 is projected by the Federal Power Commission to increase from 1,000 MW in 1980 to 6,700 MW in the year 2000.(22) For test purposes two additional 500 MW plants are assumed along the Wisconsin River in the year 2000. The sites are arbitrarily placed at the Wisconsin Rapids and Wisconsin Dells flow gaging stations. A 700 MW unit is located at Muscoda. The average annual effect near the outfall of the hypothetical plants decreases downstream from 1.6°C at Wisconsin Rapids to 1.1°C at Muscoda. The residual effect of 0.4°C at the mouth of the river would be due to the Muscoda plant since no residual effect was calculated upstream of the Muscoda outfall, see Figure 11.

The Water Quality Standards for the State of Wisconsin place a 32°C (89°F) maximum temperature on the waters of the Wisconsin River.(30) A 2.8°C (5°F) change from background is also specified, except for reaches

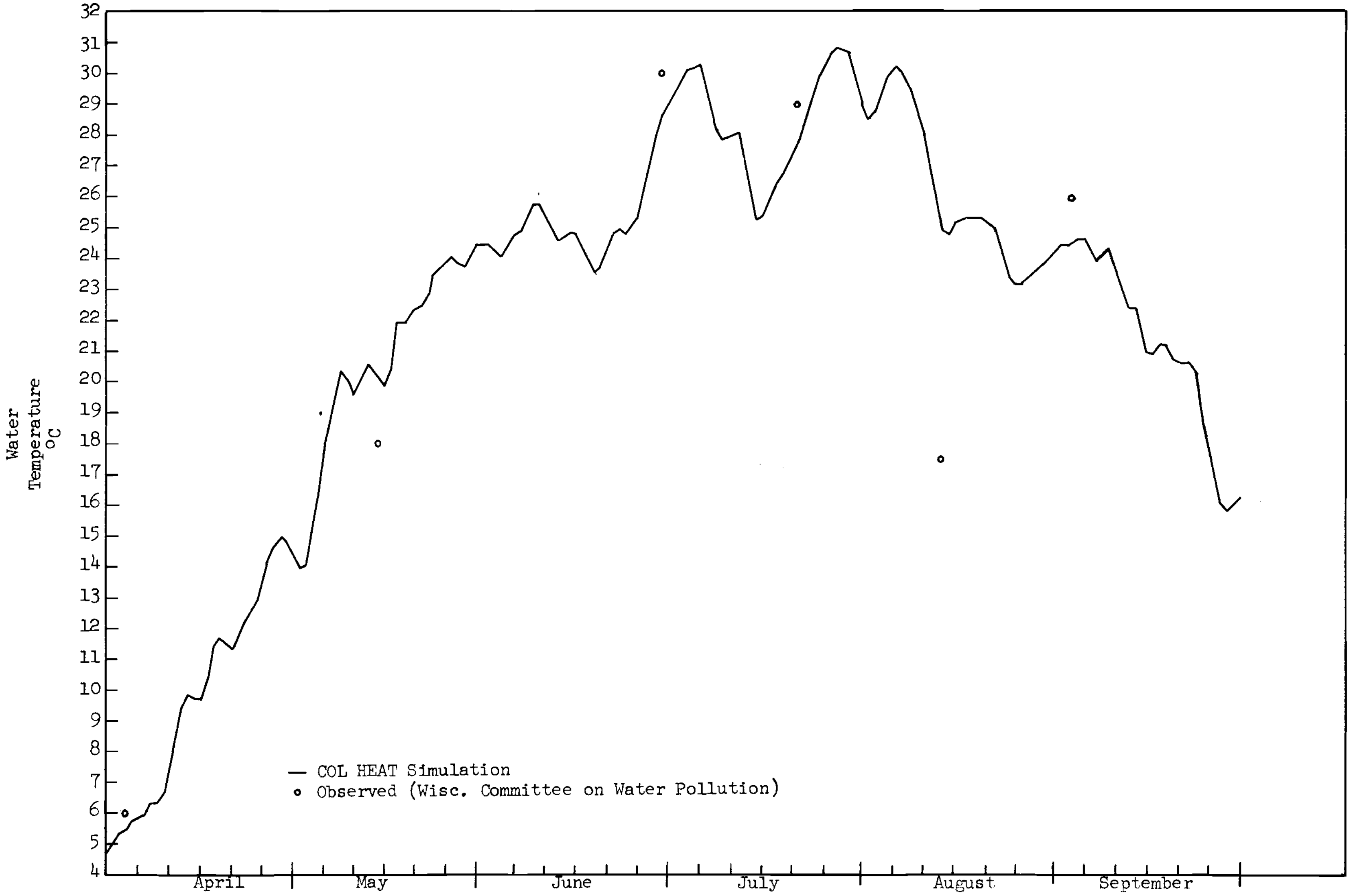


FIGURE 10. *Wisconsin River at Bridgeport-Comparison of 1964 Measured and Computed Temperatures*

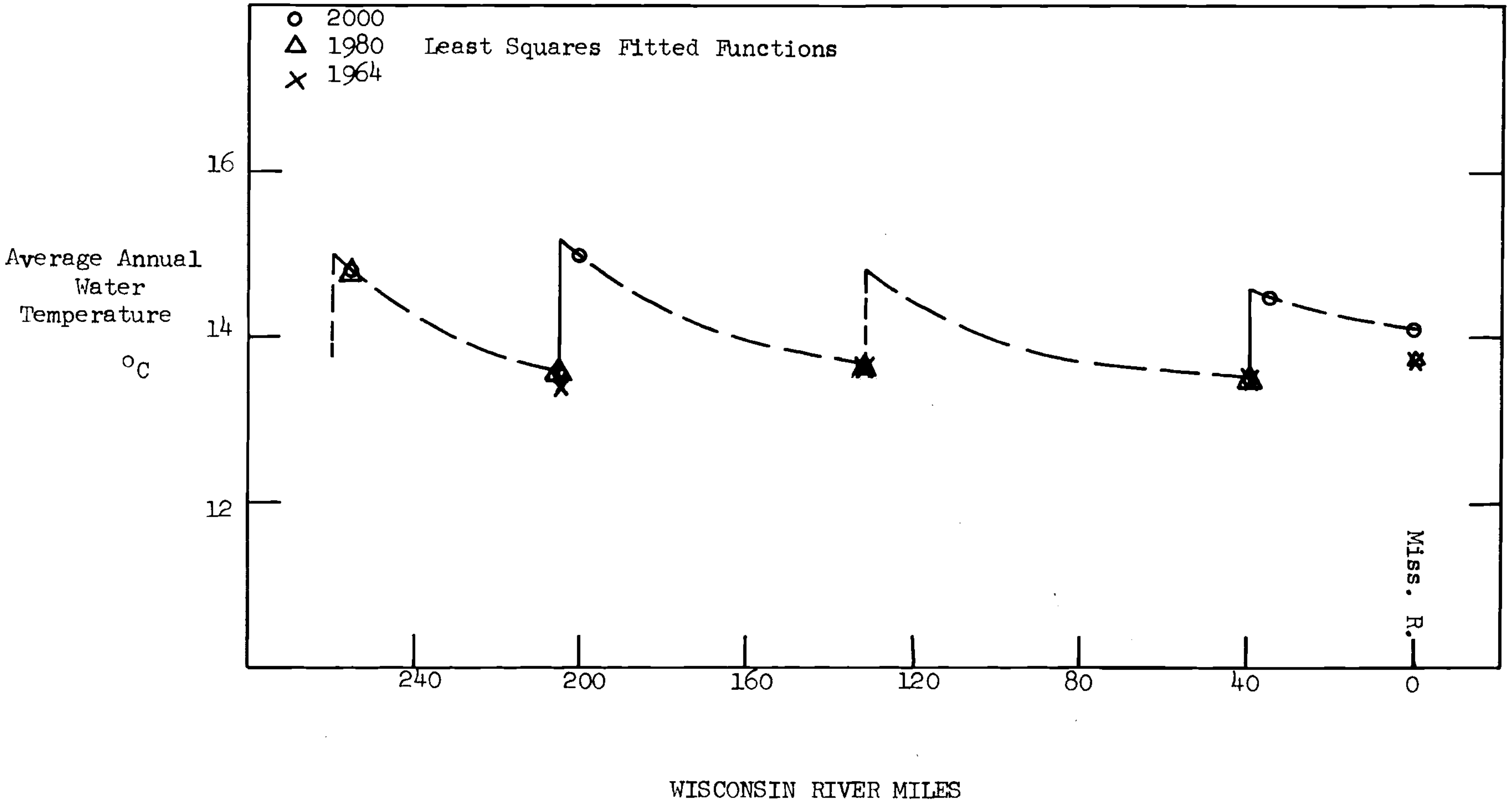


FIGURE 11. *Equilibration Profile, Wisconsin River*

designated for industrial processes and cooling purposes. The excepted reaches **extend** from Rothschild Dam (RM 259) to State Highway 34 (RM 242), from Upper Stevens Point Dam (RM 224) to Mill Creek (RM 219) and from Biron Dam (RM 212) to 5 miles south of the south Wood County line (RM 189). The hypothetical plants located at Rothschild and Wisconsin Rapids are within the areas designated for industrial processes and cooling. Because the Rothschild calculated daily temperatures were determined near the input end of the model, and as a result would be affected by an bias introduced by the partially synthetic daily input temperatures, no statement can be made concerning the relationship of the calculated temperatures to the 32°C Standard. The calculated temperatures at Wisconsin Rapids exceed 32°C 3 times in June, 15 times in July and 3 times in August. The maximum temperature of 34°C occurs in late July. At Muscoda the calculated temperatures in late July are marginal with respect to the 32°C Standard. The temperature changes from background are marginal with respect to the 2.8°C Standard on five occasions in July and August.

Rock River

The Rock River flows from a headwater region between Madison and Milwaukee in southern Wisconsin to the Quad Cities area of northwestern Illinois. It traverses a region in which both industry and agriculture are important features of the economy. Daily average flow data were available for 1964 from U. S. Geological Survey Publications for gaging stations at Afton (RM 173), Rockton (RM 157), Como (RM 68) and Joslin (RM 27).(8,9) The annual average flow at Joslin is 5,257 cfs; the 1964 average was 2,626 cfs, 50 percent of normal. Cross-section data were available only for a 5 mile reach near the confluence with the Mississippi River, at South

Rock Island. Consequently, cross-sections for computational purposes were estimated by utilizing topographic maps and flow data. A field examination of the Rock River in the Janesville-Beloit-Rockford area and the Joslin-Quad Cities area also provided information for the cross-section estimates.

Simulation

The only 1964 observed water temperatures that were secured for the simulation of the temperature regimen of the Rock River were collected by the Committee on Water Pollution of the State of Wisconsin at sampling stations near Lake Koshkonong and at Afton. The Afton data (approximately 1 point per month) were used to create a synthetic daily record for input temperatures to the model of the 173 mile segment of the river upstream of the Quad Cities. No water temperatures were obtained for the lower reaches of the stream. Consequently, any bias that would have been introduced due to factors such as seepage of groundwater or shading would have been undetected.

Projected Conditions

In 1964 the fossil fueled steam generating capacity along the Rock River was 650 MW.(22) Approximately one-third of the capacity was located in Wisconsin (Power Subarea 13) and two-thirds in Illinois (PSA 14). Between 1960 and 1980 the Federal Power Commission has forecast a fourfold increase in fossil fueled generating capacity in PSA 13 and a 60 percent increase in PSA 14. Only a minor change in energy production is expected in PSA 14, however. The effect of this would be that no significant change in residual temperatures at the mouth of the Rock River would be expected by 1980. Between 1980 and 2000 nuclear generating capacity in

PSA 14 is projected to increase from 11,000 MW to 52,800 MW. Energy production by fossil fueled plants in the year 2000 is expected to be negligible in PSA 14 and to fall below 1960 levels in PSA 13. In order to test the potential effect of nuclear power plants on the Rock River, 500 MW units are assumed at Rockford (RM 137) and at Dixon (RM 88) for the year 2000. The average annual effect of these hypothetical plants is shown in Figure 12. At Rockford the average change near the plant outfall would be 2.5°C and at Dixon 1.8°C. The residual effect at the mouth of the river would be negligible. During the months of March, April and May, when the flow was above average for the 1964 calendar year, the change in temperature near the outfall would be below average. In general, the temperature change during the other months would be above average. The maximum change from the 1964 regimen was approximately 5°C at Rockford and 3.5°C at Dixon. Rock River flows during 1964 appeared to be more regular than the flows of most of the other streams in the Mississippi Basin; the calculated changes in water temperatures due to thermal effluents correspondingly show less variation from day to day.

The Water Quality Standards of the State of Illinois, Sanitary Water Board place a 32°C (90°F) maximum on the Rock River from April through November. The calculated base 1964 temperatures (without heated effluents) for the mid-summer period, especially July, were marginal with respect to the indicated maximum. Consequently, special requirements may be necessary for 500 MW, or larger, steam plants, which would utilize Rock River water for condenser cooling.

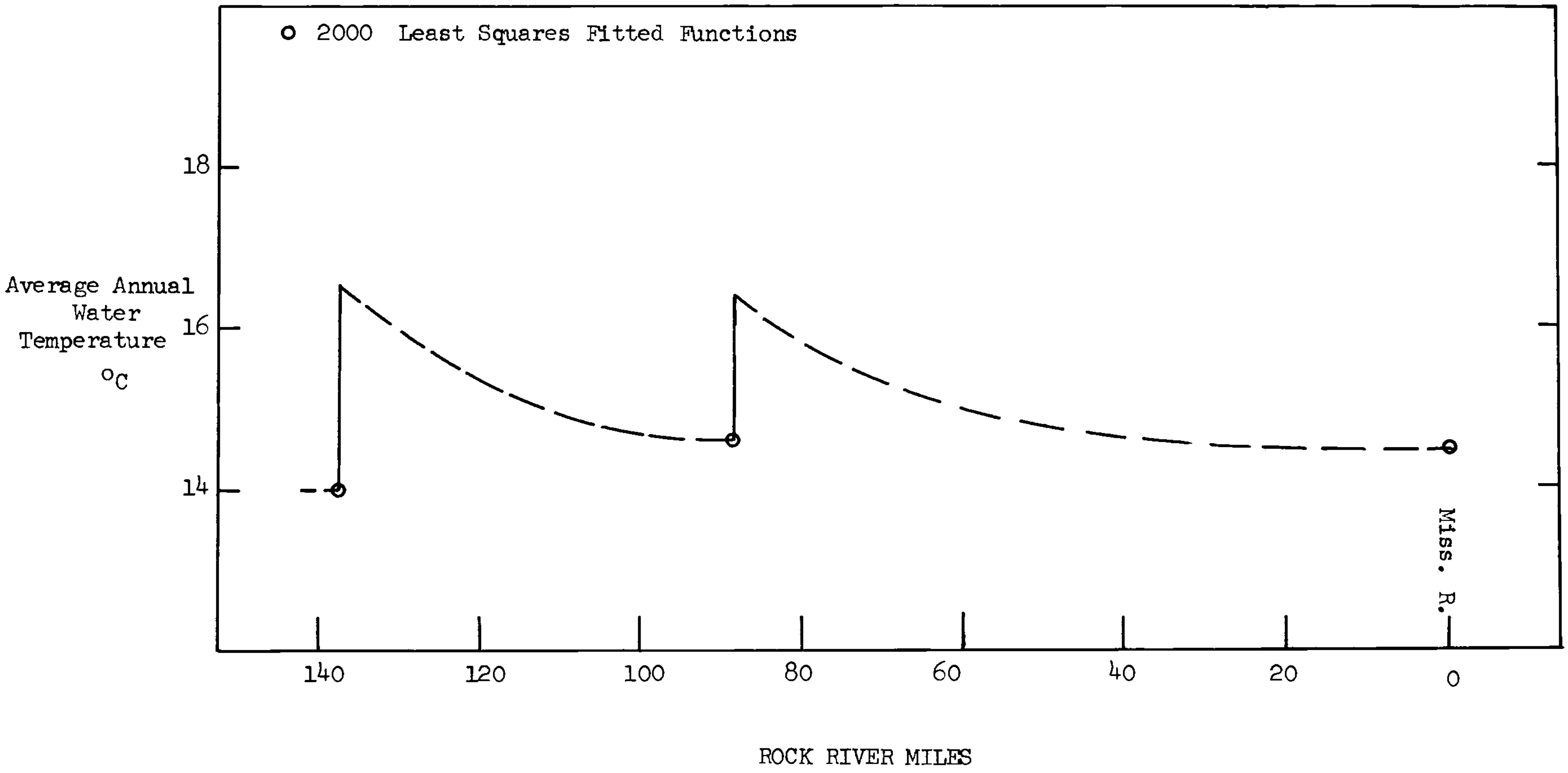


FIGURE 12. *Equilibration Profile, Rock River*

Cedar-Iowa River

The Cedar River has its headwaters in the farmlands of southern Minnesota, near the cities of Albert Lea and Austin. It follows a southeasterly course into and through the northeastern part of Iowa toward its confluence with the Mississippi, downstream of Lock and Dam No. 17 (Mississippi River Mile 434). The upper half of its long, narrow basin is featured by low topographic relief. The lower half of the basin, downstream of Waterloo, is characterized by increasing relief as the hills and bluffs, which border the Mississippi River, are approached. Despite increasing urbanization, the stream traverses a region that remains primarily devoted to agriculture. Cedar-Iowa daily average flow data were available for the calendar year 1964 from U. S. Geological Survey gaging stations at Janesville (RM 232), Waterloo (RM 217), Cedar Rapids (RM 142), Conesville (RM 40) and Wapello (RM 16).(10,12) The average annual combined Iowa and Cedar River flow at Wapello is 6,177 cfs; the 1964 average was 2,659, 42 percent of normal. The 1964 flow at Conesville, on the Cedar River Branch of the Cedar-Iowa River System, was 1,618 cfs. Flow profiles were secured from the U. S. Army, Corps of Engineers for a 242 mile section of the Cedar River. However, cross-section data were not available. The stream cross-sections, for computational purposes, were estimated from topographic maps and flow data.

Simulation

Daily average water temperatures for 1964 were available for the Shell Rock River at a U. S. Geological Survey sampling station, 11 miles upstream from the confluence with the Cedar River (Cedar-Iowa RM 228).(11,12) The 1964 average flow of the Shell Rock was approximately

350 cfs, compared with 280 cfs for the Cedar, above the confluence of the two streams. Because the initial point is arbitrary, the Shell Rock temperatures are used as input data in the model. No observed temperatures near the mouth of the Cedar or of the Iowa were secured for verification of the simulation. Consequently, it is not known whether modifying factors, such as groundwater or shading, influence the output temperatures.

Projected Conditions

No significant change in thermal loading between 1964 and 1970 was assumed for the Cedar River Basin. In 1973 a 550 MW nuclear steam plant is scheduled to go into operation near Cedar Rapids. A second unit is also planned for the same site.(22) Figure 13 illustrates the potential average effects due to flow through cooling of a single unit and the combined units, on the 1964 stream regimen. The single unit is assumed to represent 1980 conditions and the combined units 2000 conditions. In 1980 the effect near the plant outfall would average 4.9°C. The maximum temperatures near the plant outfall would be approximately 37°C and would be observed in the latter part of July. Ice formation (based on average daily conditions) would be reduced from 83 days in 1964 to 9 days in 1980. The residual effect at the mouth of the Iowa River in the 1980 simulation was indistinguishable from background. The average change in river temperature for the year 2000 simulation is 11°C near the plant outfall. The maximum for the year would be approximately 44°C. The formation of ice would be eliminated near the plant under the hypothetical year 2000 thermal loads. The residual effect 147 miles downstream, at the mouth of the Iowa River, averages 0.2°C.

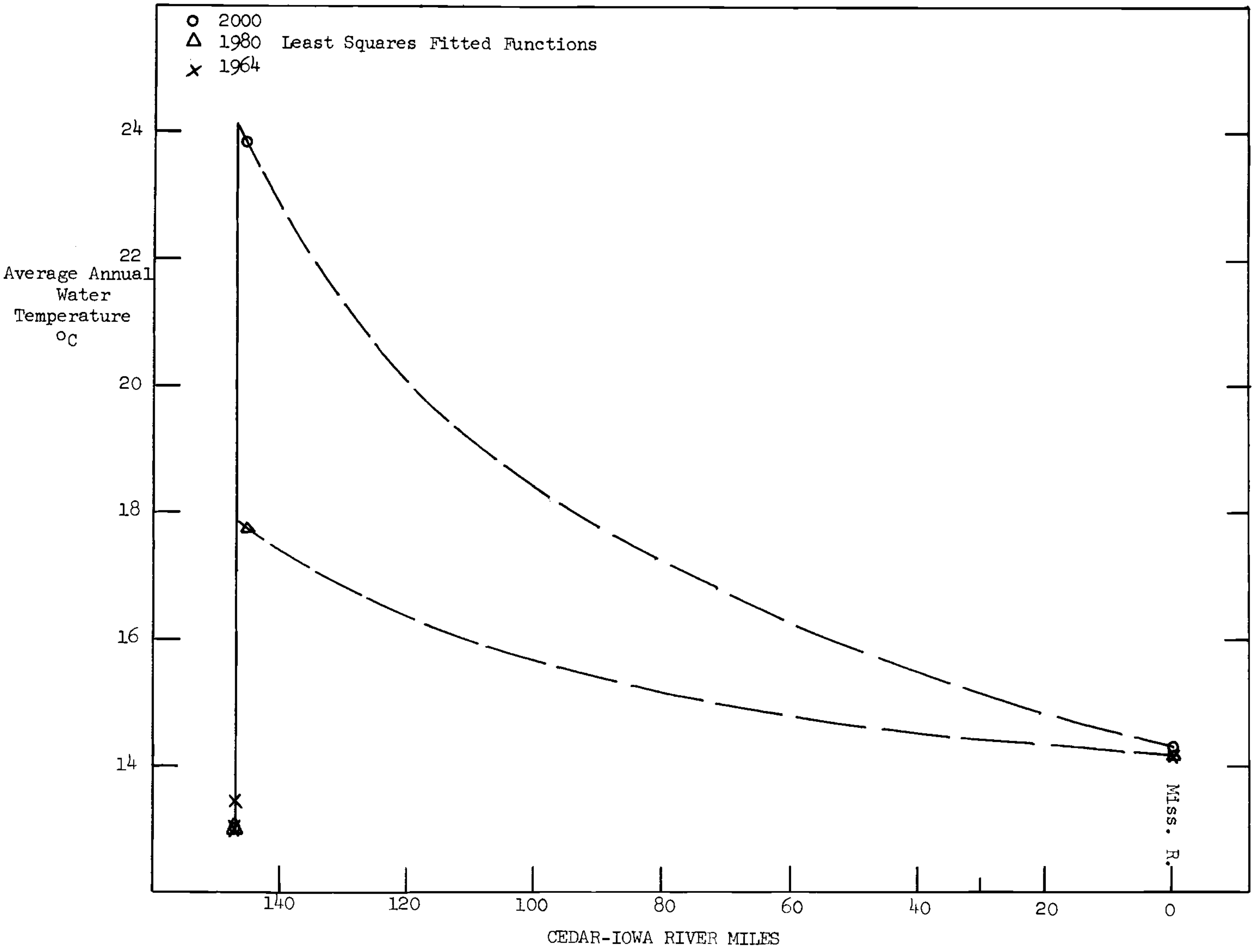


FIGURE 13. *Equilibration Profile, Cedar-Iowa River*

The State of Iowa Water Quality Standards had not been received at the writing of this report. Consequently, the relationship of the potential thermal effects of the hypothetical loads to the temperature standards cannot be examined at this time.

Des Moines River

The Des Moines River has its headwaters area in the farmlands of southwestern Minnesota. From there it flows southeastward into and across central Iowa to the southeastern corner of the state, where it joins the Mississippi near Keokuk (RM 361). Except for the Des Moines area, where urbanization is significant, the basin remains oriented toward agriculture. The land is largely rolling to gently rolling prairie, except for the hill and bluff country near the Mississippi River. The flow is largely from runoff of surface water although there appears to be significant seepage of groundwater under low flow conditions. Flow data were obtained for U. S. Geological Survey gaging stations at Saylorville (RM 211), Des Moines (RM 201), Tracy (RM 130), Ottumwa (RM 94) and Keosauqua (RM 51).(10,12) The mean annual flow at Keosauqua is 5,251 cfs; the 1964 average was 3,316 cfs, 63 percent of normal. Flow profiles were available from the U. S. Army Corps of Engineers for the 211 mile section of the river which was simulated in this study. The flow profiles and other flow data were used in conjunction with daily average flow data, travel time data and topographic maps to estimate the cross-sections over all except the lowermost 21 miles of the Des Moines River. Cross-section charts were available for the 21 mile section upstream of the mouth of the river.

Simulation

Daily average 1964 river temperatures were available for the U. S. Geological Survey gaging station at Saylorville (RM 211).(11,12) These data were utilized as input temperatures to the model. Temperatures were not obtained for the lower reaches of the stream. Thus, the extent to which groundwater modified the river temperatures is unknown. The fact that the Des Moines flow was 63 percent of normal, compared with 50 percent for the Rock, 42 percent for the Iowa and 55 percent for the Illinois, indicates a possible significant groundwater contribution to base flow during 1964.

Projected Conditions

In 1964 steam generating plants, with a total capacity of 593 MW, utilized Des Moines River water for cooling purposes. Approximately 60 percent of the capacity was located near the city of Des Moines.

Projected nuclear capacity along the Des Moines River is expected to exhibit a similar pattern to that for the Cedar River at Cedar Rapids. The first nuclear steam generating plant, with a capacity of 500 to 750 MW is scheduled for operation in 1975 near Des Moines. A second unit is anticipated for later production, so that by the year 2000 both units should be in operation. For simulation purposes a 500 MW capacity was assumed for 1980; a capacity of 1,000 MW was assumed for the year 2000. The average effect of these units on the 1964 regimen of the Des Moines River is illustrated in Figure 14. An average change of 3.5°C, compared with 1964, is noted near the plant for the 1980 simulation and 8°C for the 2000 simulation. The residual effect at the outlet of the river is calculated at 0.1°C in 1980 and 0.2°C in 2000. In 1964 a 339 MW fossil fuel generating plant was in operation in the Des Moines area. Its effect, with an assumed capacity factor of 42 percent and an efficiency of 40 percent, is also shown in Figure 14. The fossil fuel plant is arbitrarily assumed to be on a standby basis by 1980.

As indicated previously, the Iowa Water Quality Standards were not available at the writing of this report. The State of Missouri Standards, which apply to the interstate portion of the Des Moines River (from the mouth to Mile 30), state that the stream temperature shall not exceed 34°C (93°F) due to effluents and that effluents shall not elevate or depress the average cross-section temperature of the stream more than 2.8°C (5°F).(27)

Illinois River

The Illinois River is the largest tributary stream of the Upper Mississippi Basin. Its annual average flow at the Meredosia gaging station is 19,500 cfs, significantly greater than the 8,400 cfs of the next largest tributary, the Wisconsin River. The 1964 average flow was 10,640 cfs, 55 percent of normal.(11) The river itself is developed for barge traffic between the Mississippi River and the Chicago area by approximately 330 miles of slack water pools and the locks and dams of the Illinois Waterway. In 1964 a total of 30,745,131 tons were transported on the Illinois Waterway; this represented over 47 percent of the combined tonnage of the Upper Mississippi and Illinois Waterways.(31) The Waterway system is also used extensively for sanitary and industrial processes and for cooling, especially in the Chicago area. The section

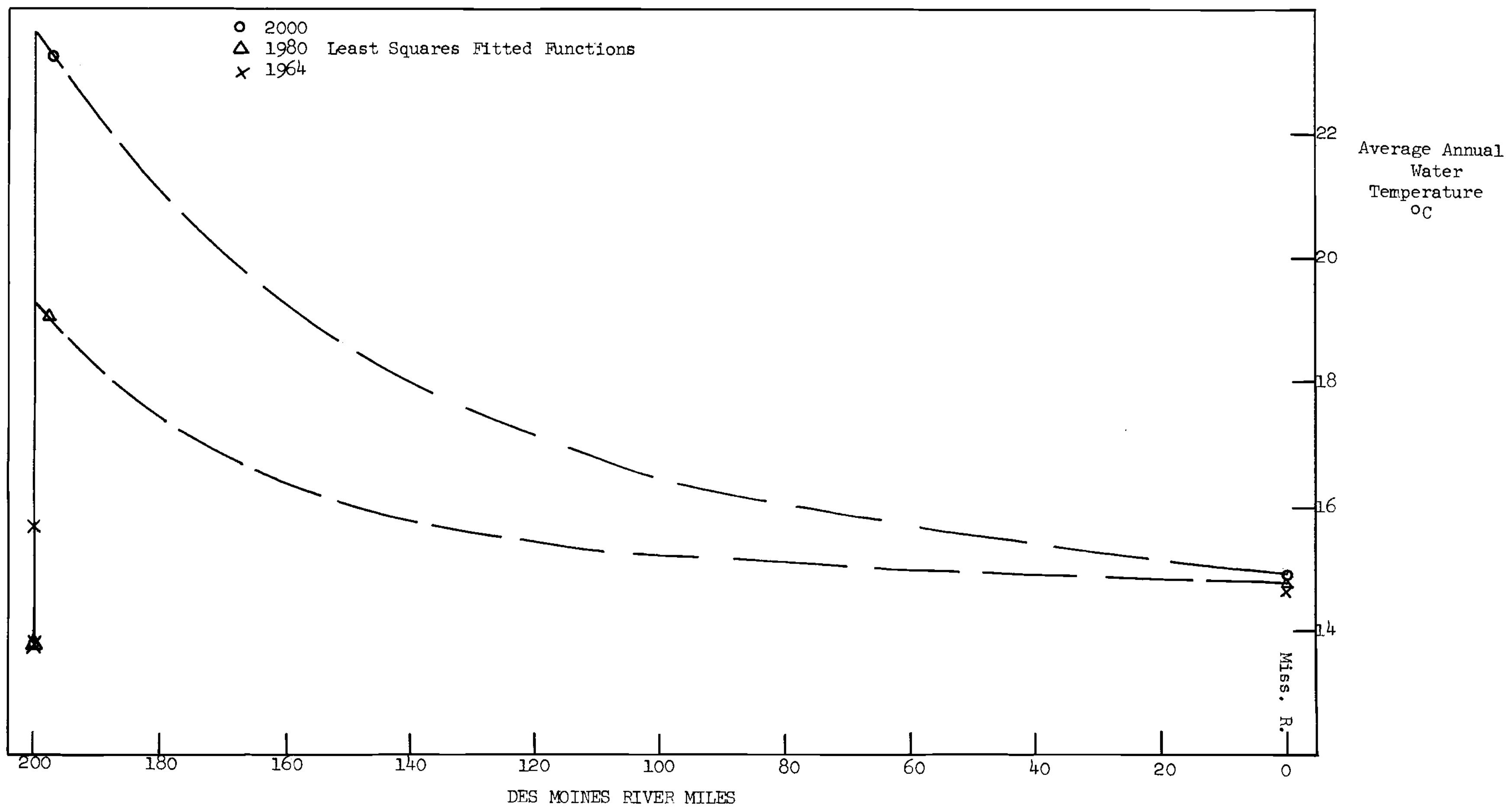


FIGURE 14. *Equilibration Profile, Des Moines River*

of the river downstream of Mile 278, which was simulated in this and related studies, traverses a region dominated by farmlands and small cities. In 1964, steam generating plants with a total capacity of 1,915 MW were located along this section of the Illinois Waterway.(32) All plants utilized flow through condenser cooling. Dresden Unit #1, with a capacity of 208.7 MW, was nuclear fueled, the remainder were fossil fueled.

Projected Conditions

Between 1964 and 1970 there is scheduled to be an increased nuclear capacity of 1,430 MW at Dresden (RM 270) and an increased fossil fueled generating capacity of 281 MW at Peoria (RM 258). The effects of these plants in the year 1970 are subjects of separate reports and will not be discussed in detail herein.(3) The residual at the mouth of the river in the 1970 simulation (compared with 1964 temperatures) would be less than 0.1°C. The FPC projects a nuclear capacity of 11,000 MW in PSA 14 by 1980. PSA 14 includes the upper reaches of the Illinois River down to River Mile 185. For test purposes a 1,500 MW unit at River Mile 230 and a 1,000 MW unit at River Mile 190 are assumed in the 1980 simulation. The Dresden Plant is included in the 1980 simulation in the form of a 3,541 MW thermal input, Monday through Friday, and a 1,968 MW thermal input over weekends. This load corresponds to Case IIIa of a previous report.(3) In PSA 40, downstream of River Mile 185, no nuclear power plants are projected for 1980. An increase of 300 MW of advected (waste) heat is the only significant change (compared with 1964 conditions) included in the lower section of the river in the 1980 simulation. Figure 15 illustrates the effects of the hypothetical inputs upon the

1964 stream regimen. In 1964 the river as a whole tended to exhibit a cooling trend from the Chicago area to Peoria and then, as a result of advected heat in the Peoria area and downstream points and also because of the moderating effect of climate in a southerly direction, the river exhibited a warming trend from Peoria to the mouth. A feature of the 1980 simulation worthy of a note is the apparent greater capacity of the Lake Peoria region to dissipate waste heat than other sections of the river. In the year 2000 the nuclear capacity is projected to be 52,800 MW in PSA 14 and 8,400 in PSA 40. Fossil fuel energy production is projected to be only 68 percent of 1960 loads in PSA 40 and negligible in PSA 14. For test purposes six nuclear generating plants are assumed along the Illinois River in the year 2000 simulation: 2,500 MW at RM 270, 2500 MW at RM 230, 4,000 MW at RM 190, 2,500 MW at RM 119, 2,000 MW at RM 74 and 2,000 MW at RM 40. The Capacity Factor assumed for all nuclear units is 57 percent, which is the CF forecast for PSA 14 in the year 2000. At RM 119 and 74 a fossil fuel capacity of 2,400 MW, with a Capacity Factor of 28 percent, is assumed. The average advected heat from the above units, assuming flow through cooling is as follows: RM 270 (2,100 MW), RM 230 (2,100 MW), RM 190 (3,400 MW), RM 119 (3,100 MW), RM 74 (2,700 MW), RM 40 (1,700 MW). These quantities of heat, which would represent less than one-third of the projected power output in PSA 14 and 40 are the result of an attempt to equilize the thermal peaks. It would appear that, by reducing the thermal input at RM 74 to approximately one-half the hypothetical value used herein, equilization could be approached, at least for 1964 flow and weather conditions.

The Water Quality Standards for the Illinois River specify that the water temperature shall not exceed 34°C (93°F) from the Chicago area downstream to the Fox River (RM 239). Other sectors of the river have a 32°C (90°F) Standard from April through November and 15.5°C (60°F) Standard from December through March. The Standards also specify that all waters must not exceed a 2.8°C (5°F) cumulative change from natural water temperature. In the 1980 simulation the hypothetical 1,500 MW plant at RM 230 would be marginal or exceed the 32°C maximum during the mid-summer period of the 1964 regimen. There would be an average increase in river temperatures of 6.6°C near the outfall of the Mile 230 plant; this would be 3.8°C greater, on the average, than the permissible cumulative change, if 1964 water temperatures are considered as natural water temperatures. At mile 190 the effects of a hypothetical 1,000 MW unit would be marginal during the early and latter parts of July with respect to the 32°C Standard. For the year 2000 simulation the hypothetical unit at RM 270 would not exceed the 34°C Standard. At RM 230 the effect would be marginal with respect to the 32°C Standard during the summer months with calculated temperatures attaining a maximum of 35°C in late July. A similar effect is noted for the hypothetical plants at Miles 190 and 119. At Miles 74 and 40 the thermal effluents would exceed 32°C during the summer months; the calculated maximum is 39°C. During late February and March the water temperatures near the outfall of these two plants would be marginal with respect to the 15.5°C Standard.

Mississippi River

The Upper Mississippi River extends for approximately 1,375 river miles between Lake Itasca in northern Minnesota and the confluence with

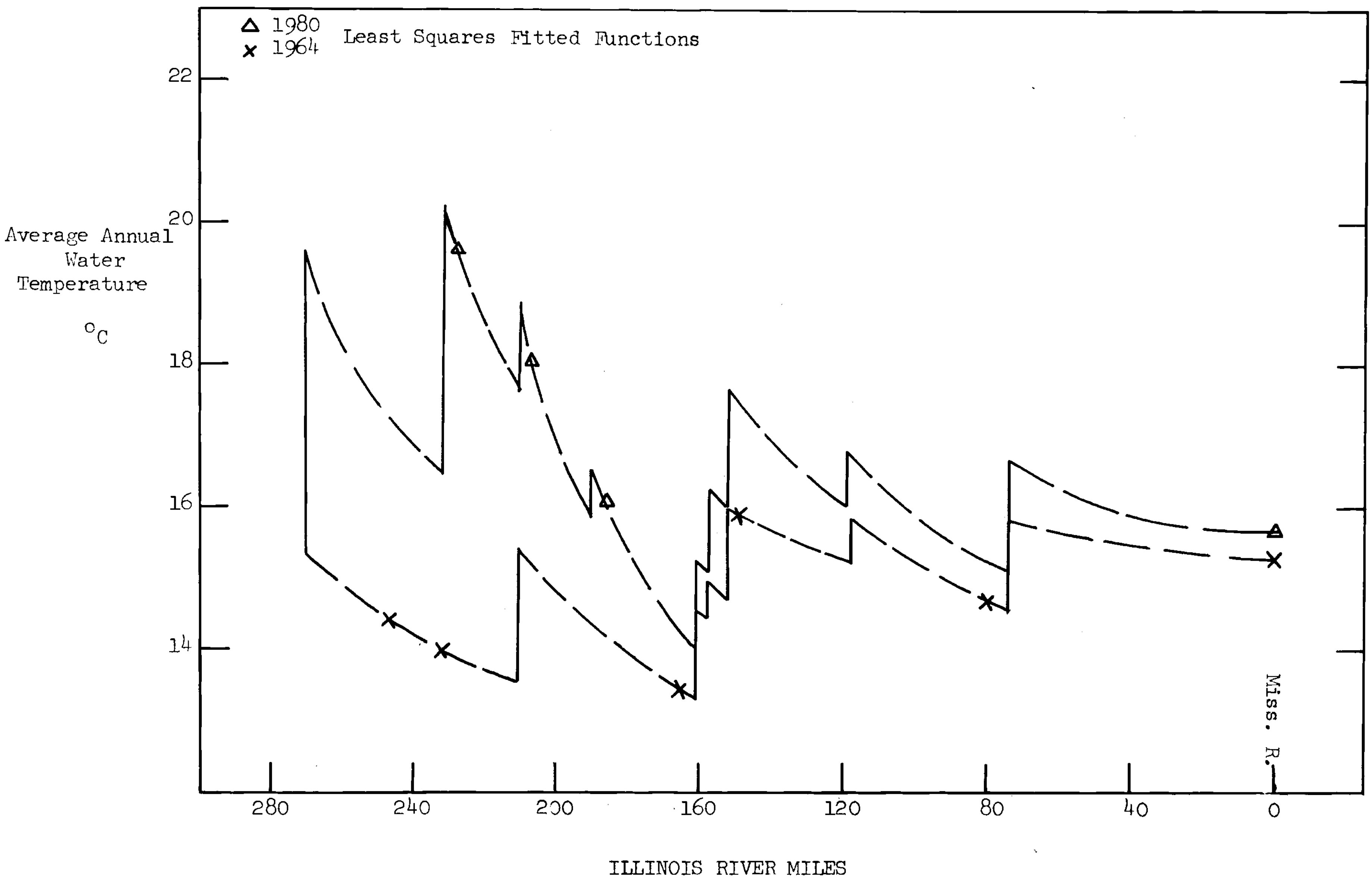


FIGURE 15. *Equilibration Profile 1980, Illinois River*

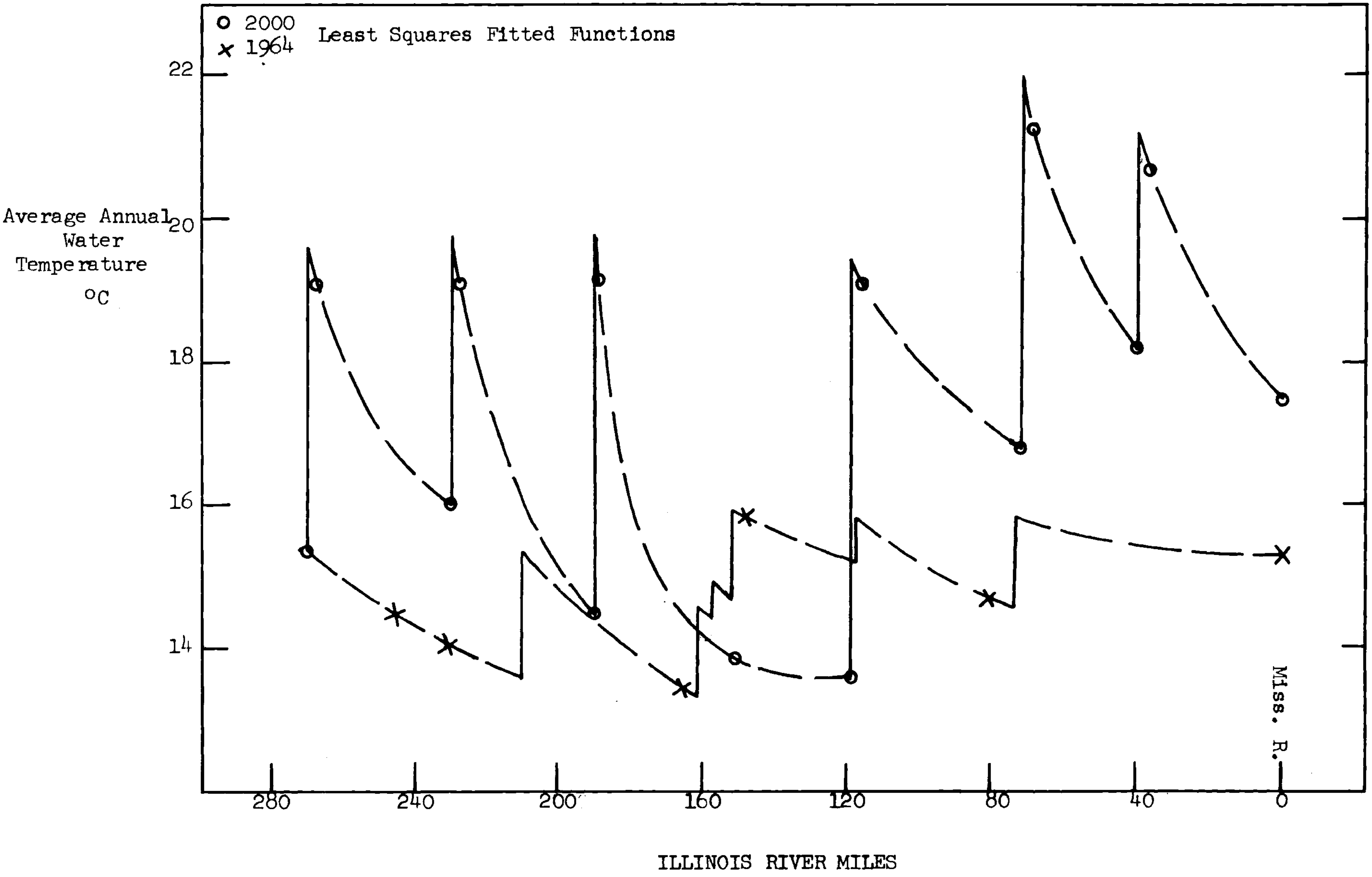


FIGURE 16. *Equilibration Profile 2000, Illinois River*

the Ohio River at Cairo, Illinois (see Figures 1,3). The uppermost 400 miles consist of a large question-mark shaped course, which traverses a region with only minor agricultural and urban development. Wood products and recreation are major industries in the area. Because of an expected low rate of development, it is assumed that no nuclear power development would be undertaken in the area in the near future. Consequently, the section selected for study lies between the gaging station at Royalton, Minnesota (RM 956) and the gaging station at Alton, Illinois (RM 203). No simulations were carried out below the confluence with the Missouri River, which merges with the Mississippi between Alton and St. Louis.

In general, the data available for simulation of the Mississippi River were good. Detailed cross-sections, river profiles and daily flow data were secured from the St. Paul, Rock Island and St. Louis Offices of the U. S. Army Corps of Engineers for the Waterway section of the River. The Upper Mississippi Waterway consists of 26 Pools lying between St. Anthony Falls Dam (RM 853) at Minneapolis and Lock and Dam No. 26 (RM 203) at Alton. Between St. Anthony Falls and Royalton, cross-sections were not available; therefore, it was necessary to estimate the river sections. The estimates were made by utilizing river flow data, travel time data and topographic maps. A field examination of the river between the Twin Cities and St. Cloud (RM 926) also provided useful information. In developing the trapezoidal sections from cross-section data 1964 flow profiles were considered so that representative surface areas and volumes could be obtained. Because the present COL HEAT model holds the dimensions of the river fixed, flood conditions are not as well simulated as normal flow. This can be accommodated by segmenting the simulation into time increments in which river sections are used that are representative of the flow during a given increment. However, no variations in river sections were considered necessary in the Mississippi simulation. Tests made with the stream dimensions greatly modified have revealed that, except for the timing of transient events, the sensitivity of the computations to errors in stream volume is small. Also, the volumes of the continuous series of reservoirs between the Twin Cities and Alton are not as greatly modified by extreme flows as the river was before the development of the present Waterway. The fact that 1964 was a relatively low flow year, with an annual (calendar year) average at Alton of only 57 percent of normal, made the assumption more valid than it would have been under conditions of unusually high flows. The 1964 average flows at several gaging stations along the Mississippi are as follows: Royalton (RM 956) - 4,483 cfs, 113 percent of normal; St. Paul (RM 839) - 7,820 cfs, 80 percent of normal; Winona (RM 726) - 18,710 cfs, 76 percent of normal; Clinton (RM 512) - 28,220 cfs, 60 percent of normal; Keokuk (RM 364) - 35,410 cfs, 58 percent of normal; and Alton (RM 203) - 53,000, 57 percent of normal.(12,14,16)

Model Verification

Simulations of 1964 summer temperatures in comparison with observed temperatures are illustrated for five locations along the Mississippi in Figures 17 through 21. These include Minneapolis (RM 848), Alma (RM 753), Moline (RM 493), Quincy (RM 325) and Alton (RM 203). No unusual modifications of the model were required to simulate conditions on the Mississippi, indicating that weather conditions are the dominating factor controlling the natural temperature of the river. Other factors, such as shading of the water surface, variations in wind velocity and groundwater, appear to be minor modifiers of the temperature regimen; an exception could be the reach upstream from Minneapolis, as indicated by a positive bias in computed July temperatures. A more detailed study would be expected to give local significance to a number of other factors.

Projected Conditions

Figure 22 illustrates the calculated average 1964 Mississippi River temperature at several points between Minneapolis and Alton. The temperatures ranged from 12.2°C on the upstream side of Minneapolis to 15.5°C at Alton. These temperatures included the residual effects of an average annual thermal load of 12,250 MW of advected heat, included in the 1964 simulation of the trunk and tributary streams, plus thermal residuals that were included indirectly in the form of observed input temperatures to the model. Also indicated in Figure 22 are calculated average temperatures for 1970, 1980 and 2000. The digital output at the points indicated by circles or other index marks in Figure 22 is compiled into a least squares sinusoidal model of the annual data, a procedure used as a method for long term trend analysis. These least squares data indicate that there would be an increase in maximum temperatures of up to 0.1°C downstream of the St. Croix River in 1970. In the Twin Cities area the effect would be approximately 0.4°C under the study assumptions. By 1980 the average increase in maximum temperatures would be approximately 0.4°C over the river as a whole. Freezing conditions would not occur in the Alton Pool under the assumptions of the 1980 simulation. The average increase in maximum temperatures in 2000, compared with 1964 temperatures, would be approximately 1.8°C. The average minimum temperature in the year 2000 would be approximately 1.3°C. It would appear that under the assumptions of the 2000 simulation that ice formation would be confined to the middle section of the River and would cover approximately a 3 week period.

The Water Quality Standards of the State of Minnesota indicate that the stream temperature shall not exceed 30°C (86°F) upstream of the Twin Cities. The maximum apparently is 32.2°C (90°F) from the Twin Cities downstream to Lock and Dam No. 2. From Lock and Dam No. 2 to Dubuque the State of Wisconsin Water Quality Standards specify a 31.7°C (89°F) limit. From Dubuque to Alton both Illinois and Missouri specify a 32.2°C (90°F) maximum. In addition, all sections of the river, with the possible exception of the Minneapolis-St. Paul area, have a requirement that effluents shall not change the water temperature from background by more than 2.8°C (5°F). Under year 2000 assumptions the average daily water temperature would be marginal to or exceed 30°C during July and August between Miles 900 and 865. The temperature increase near the hypothetical 1,500 MW plant at RM 900 would average 4.7°C. Near the assumed 2,500 MW plant at RM 839 the calculated temperatures exceed 32°C during the greater part of July and August; near Lock and Dam No. 2 the temperatures would be marginal with respect to 32°C during late July and early August of the 1964 regimen. At Mile 658 the calculated temperatures at the outfall of a hypothetical 1,000 MW plant would be marginal to or exceed 32°C during July and early August. The calculated system increase near this plant averages 1°C with respect to upstream temperatures and 2°C with respect to 1964 temperatures. Although the effluents from this plant would not cause a 2.8°C change at any time during the year, the cumulative effect of upstream units would result in a marginal condition with respect to 2.8°C. The hypothetical 200 MW plant at RM 512 would be marginal to 32°C during July and August. The system increase remains below 2.8°C. Temperatures would also be marginal with respect to 32°C near the hypothetical 1,000 MW plant at Mile 375 during the summer months. The system increase near this plant would reach a maximum of 0.8°C above the upstream temperatures; in general, the calculated change was 0.5°C or less. At Mile 215, 1 mile upstream of the confluence with the Illinois River, a similar pattern of marginal temperatures with respect to 32°C is noted in July and August of the 1964 regimen.

Figure 23 is an example of the daily variation in water temperatures under assumed 1970, 1980 and 2000 conditions.

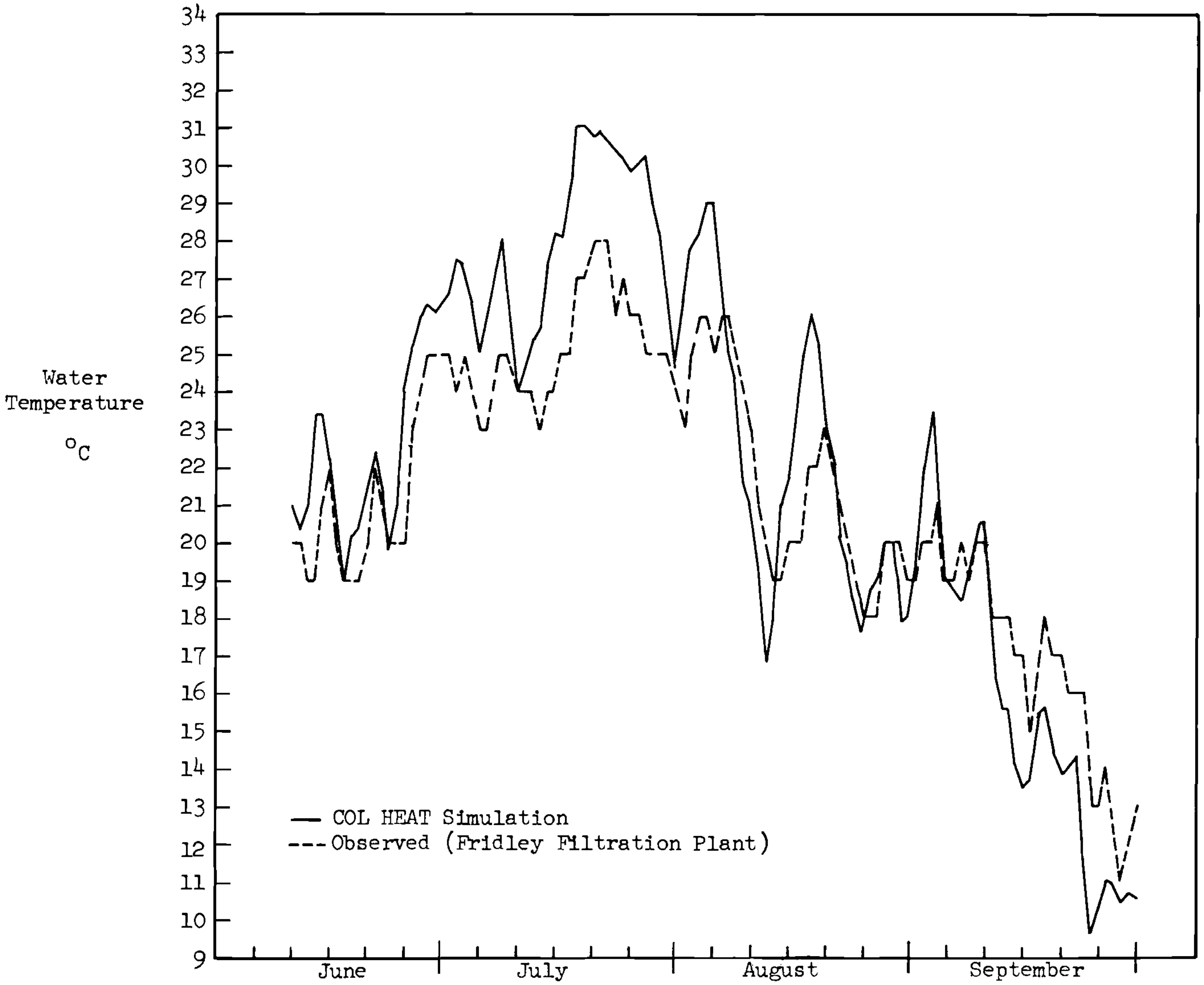


FIGURE 17. *Mississippi River at Minneapolis-Comparison of 1964 Measured and Computed Temperatures*

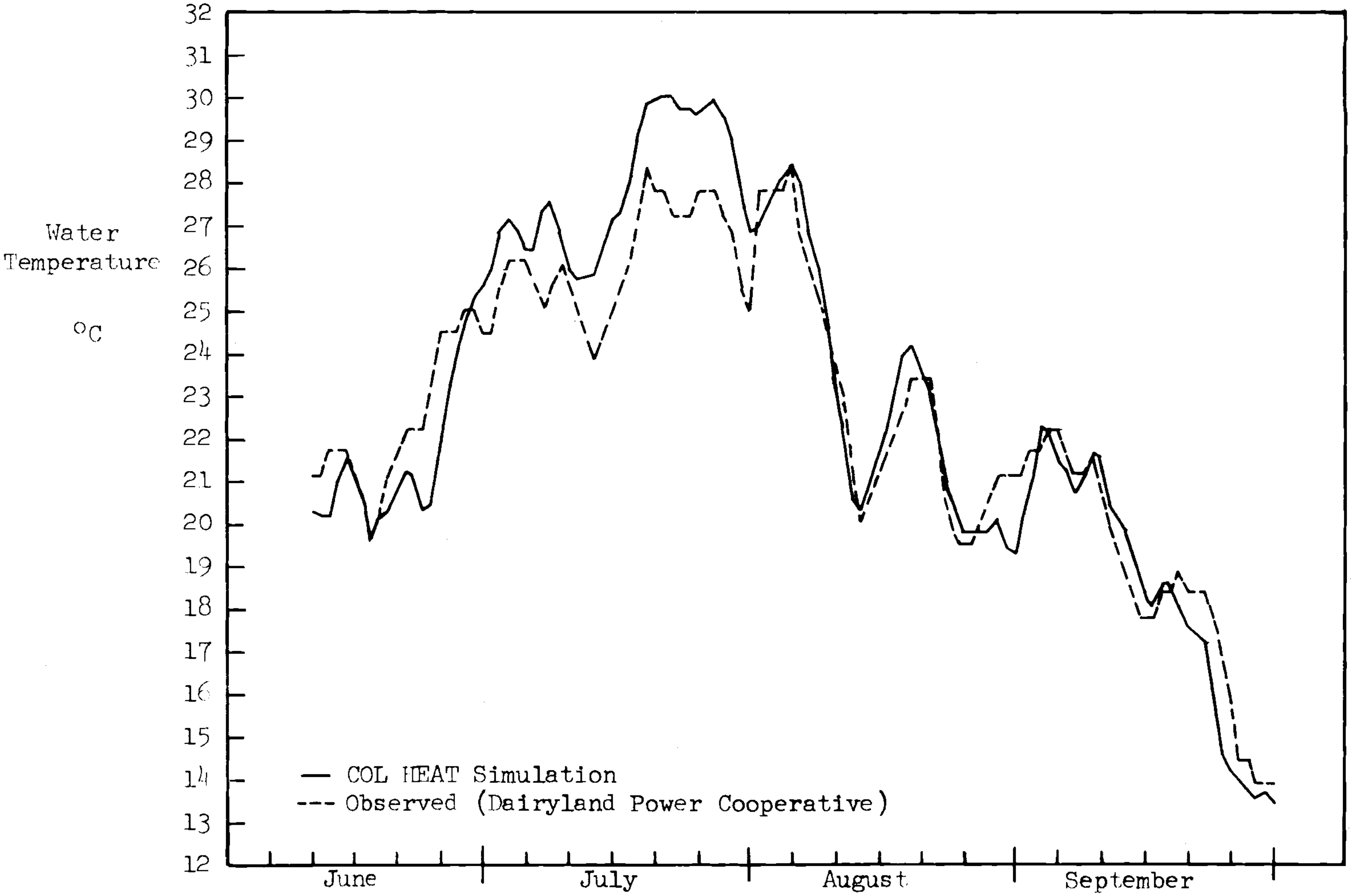
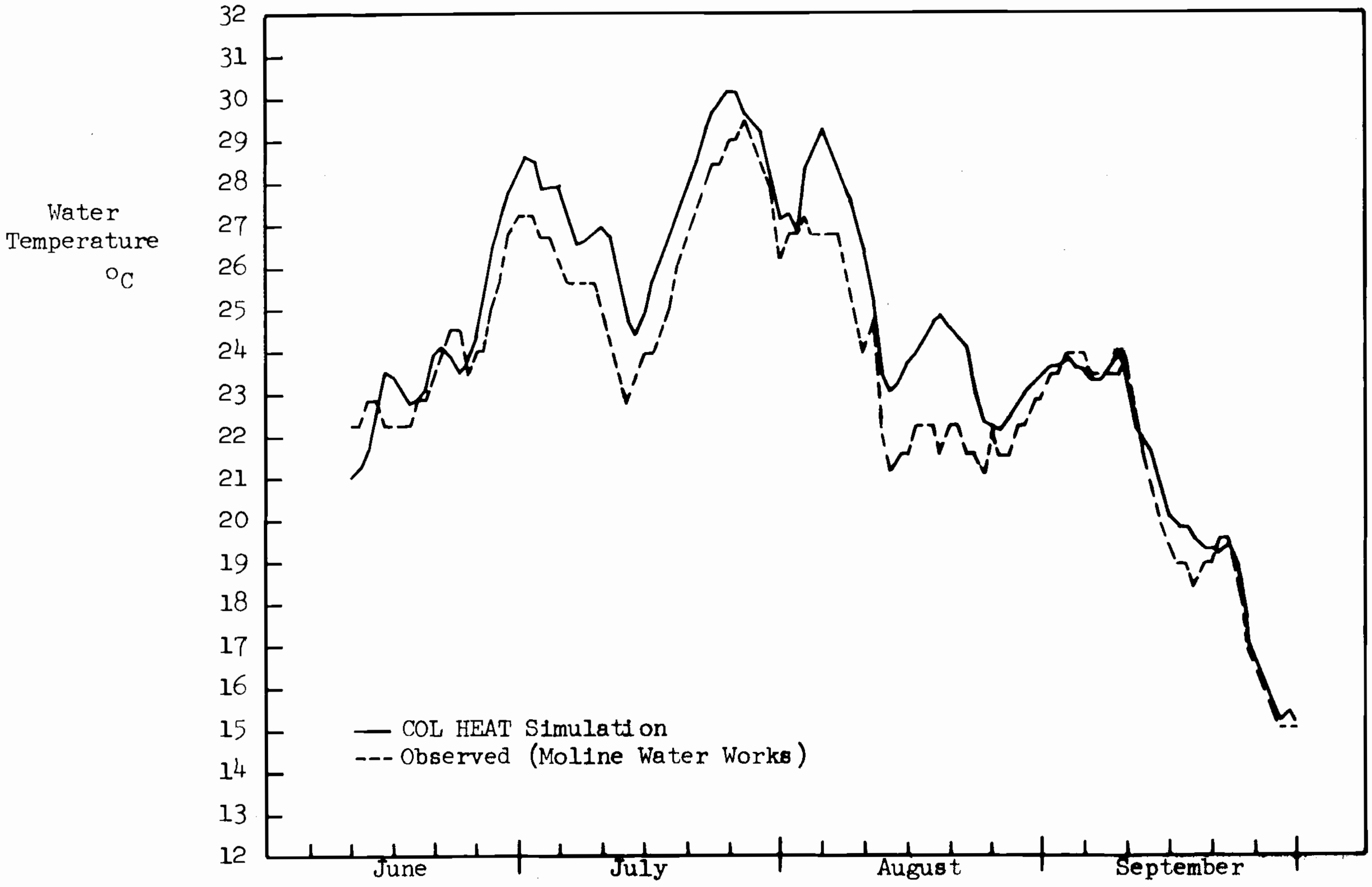


FIGURE 18. *Mississippi River at Alma-Comparison of 1964 Measured and Computed Temperatures*



<u>FIGURE 19</u>. Mississippi River at Moline-Comparison of 1964 Measured and Computed Temperatures

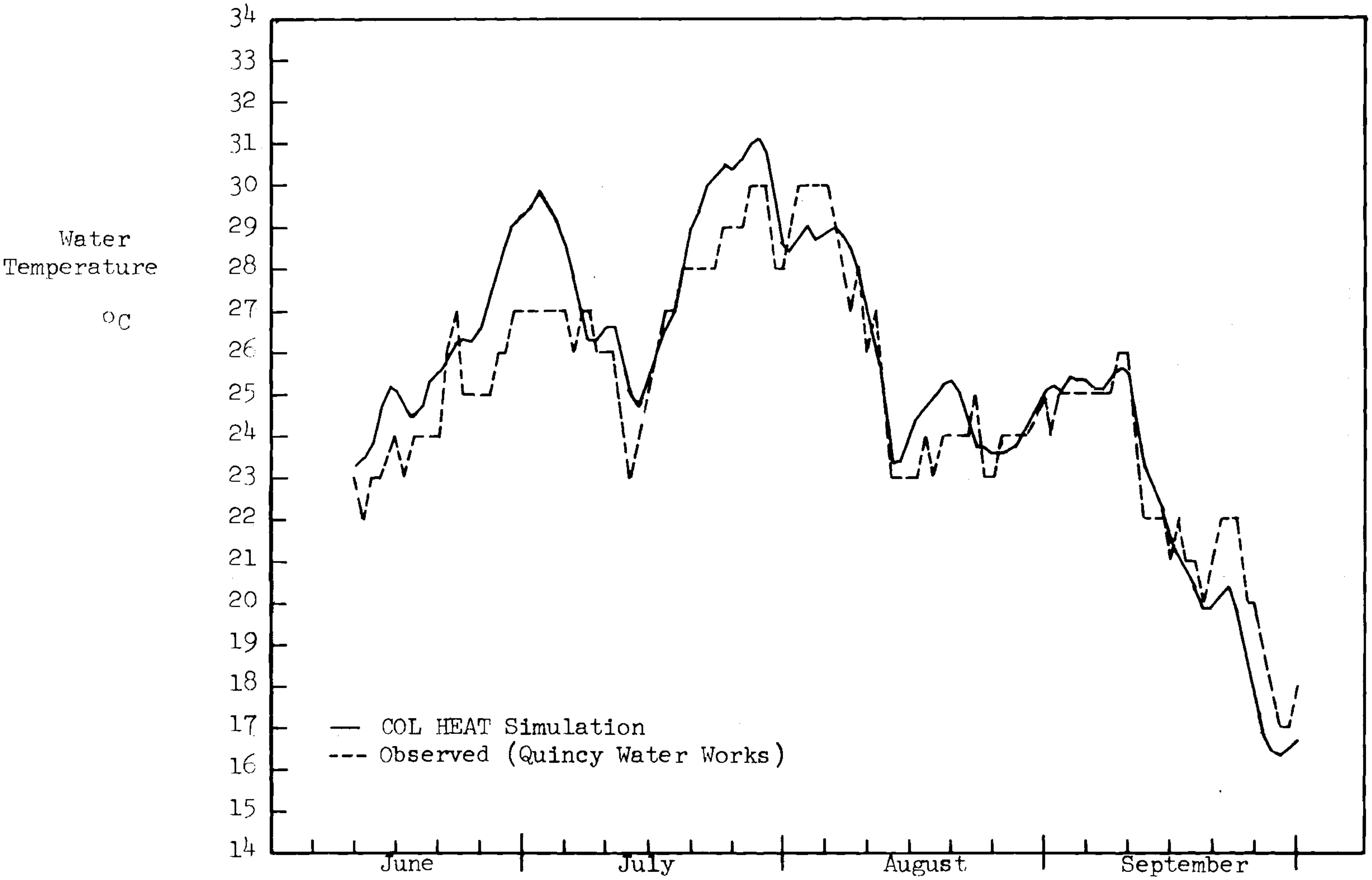


FIGURE 20. *Mississippi River at Quincy-Comparison of 1964 Measured and Computed Temperatures*

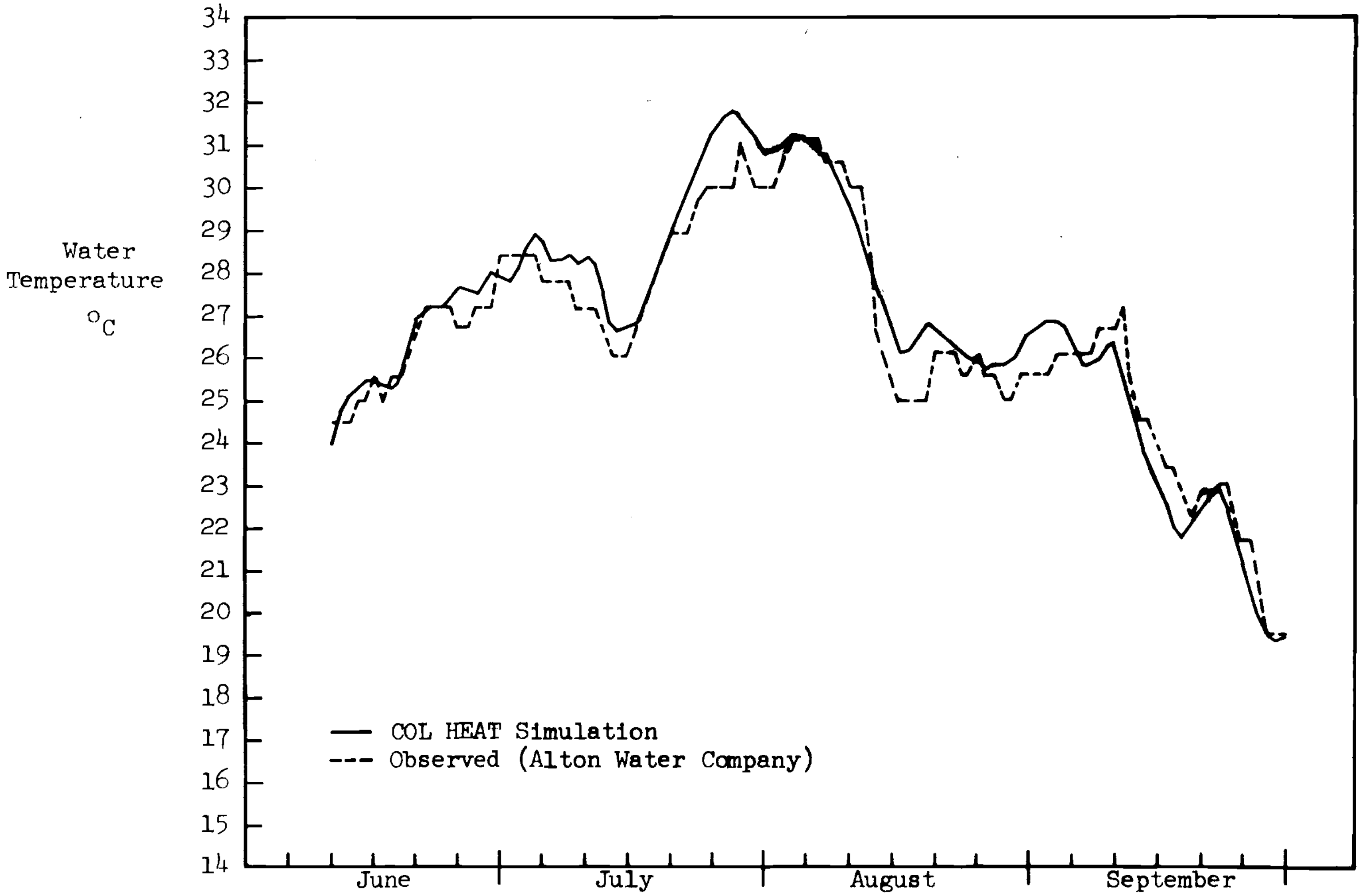


FIGURE 21. *Mississippi River at Alton-Comparison of 1964 Measured and Computed Temperatures*

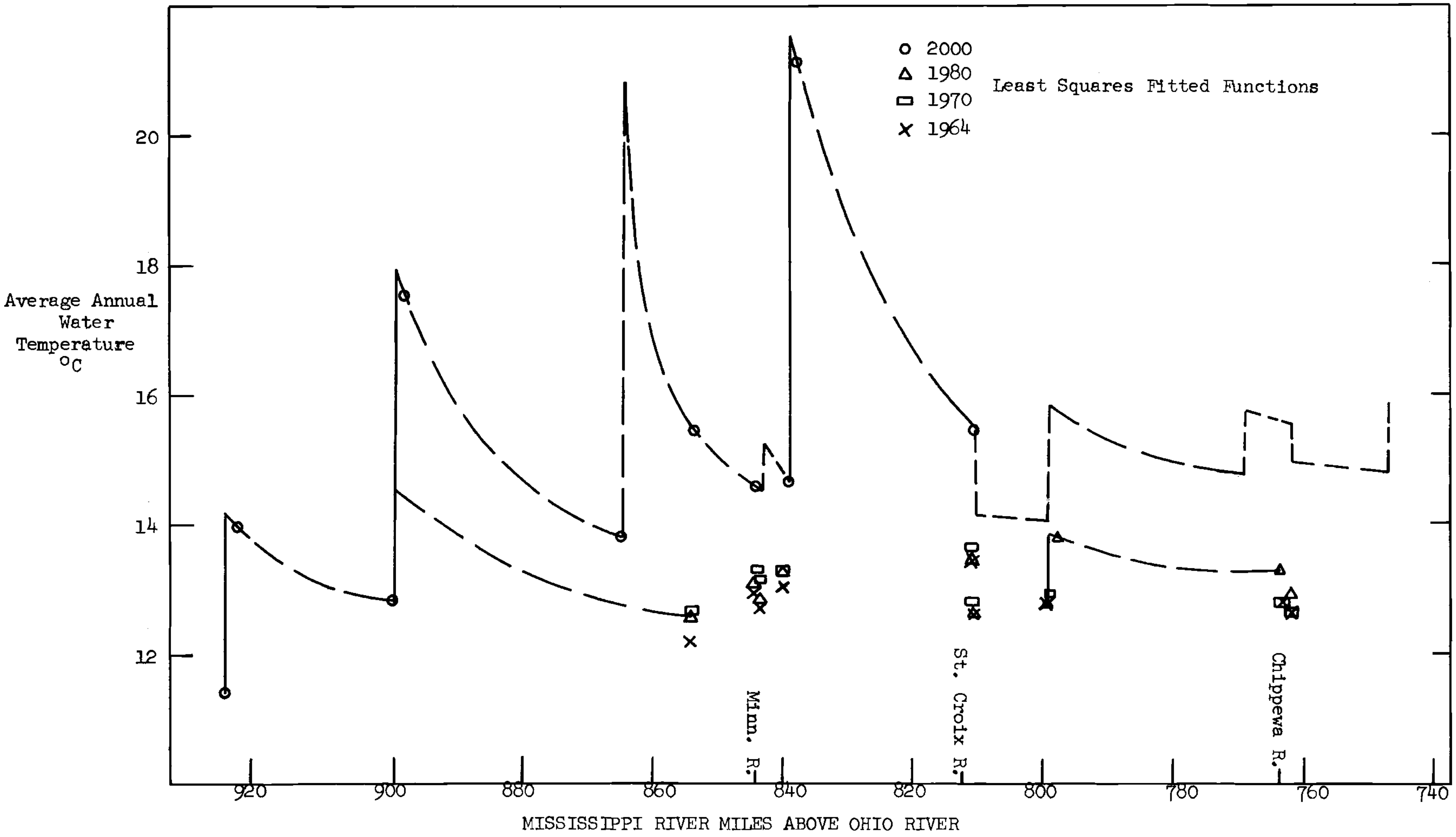


FIGURE 22a. Equilibration Profile, Mississippi River

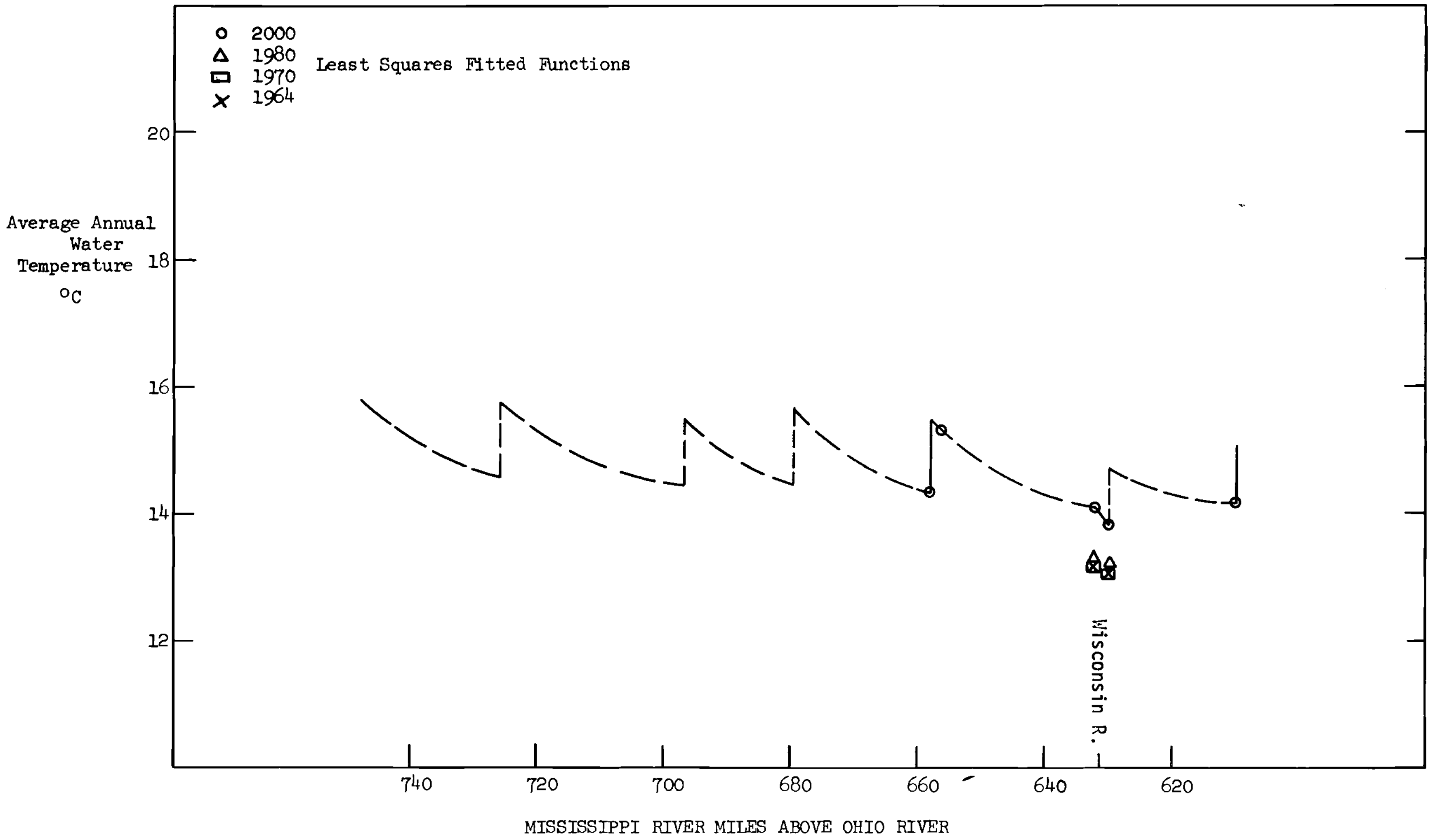


FIGURE 22b. *Equilibration Profile, Mississippi River*

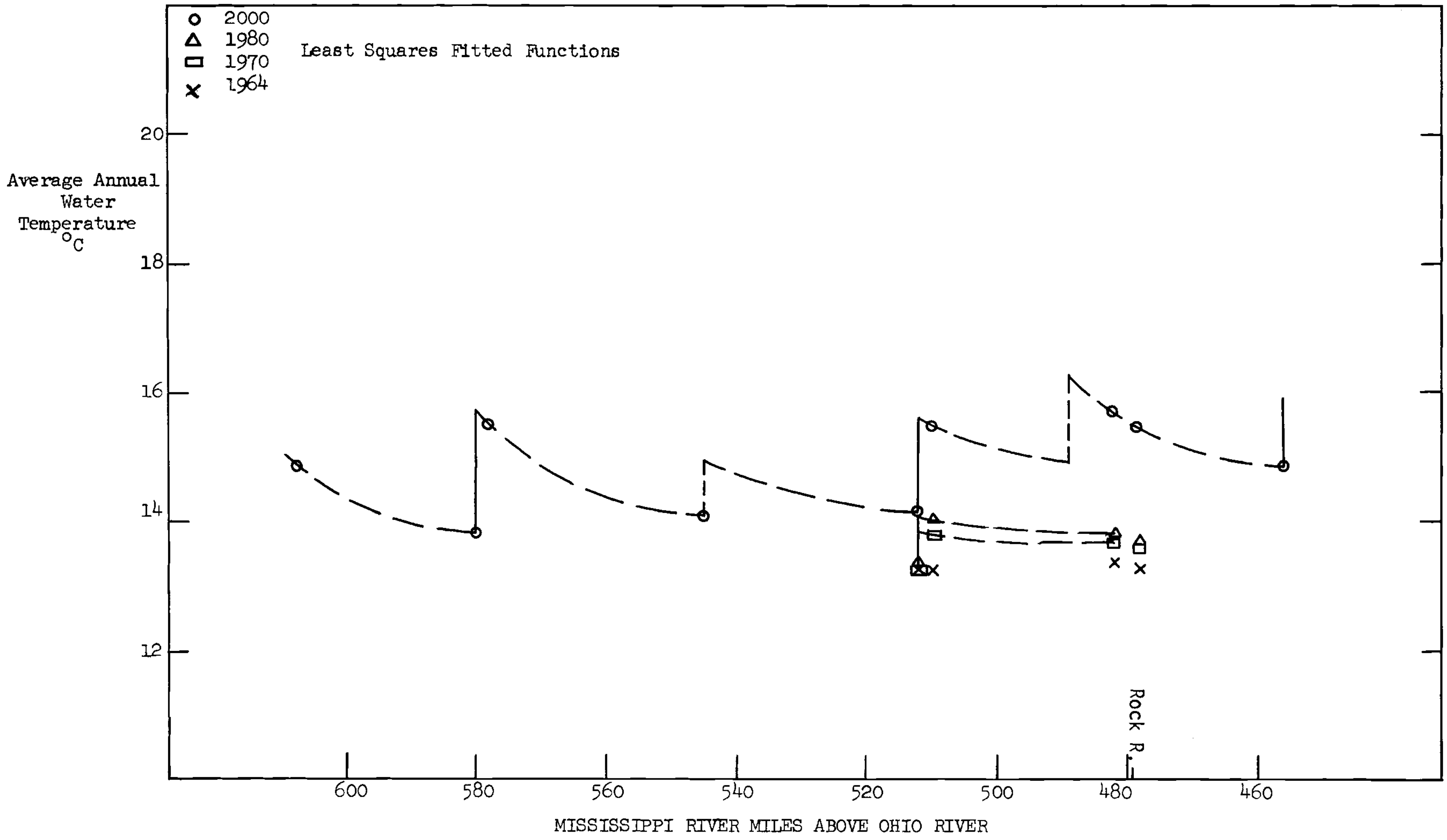


FIGURE 22c. Equilibration Profile, Mississippi River

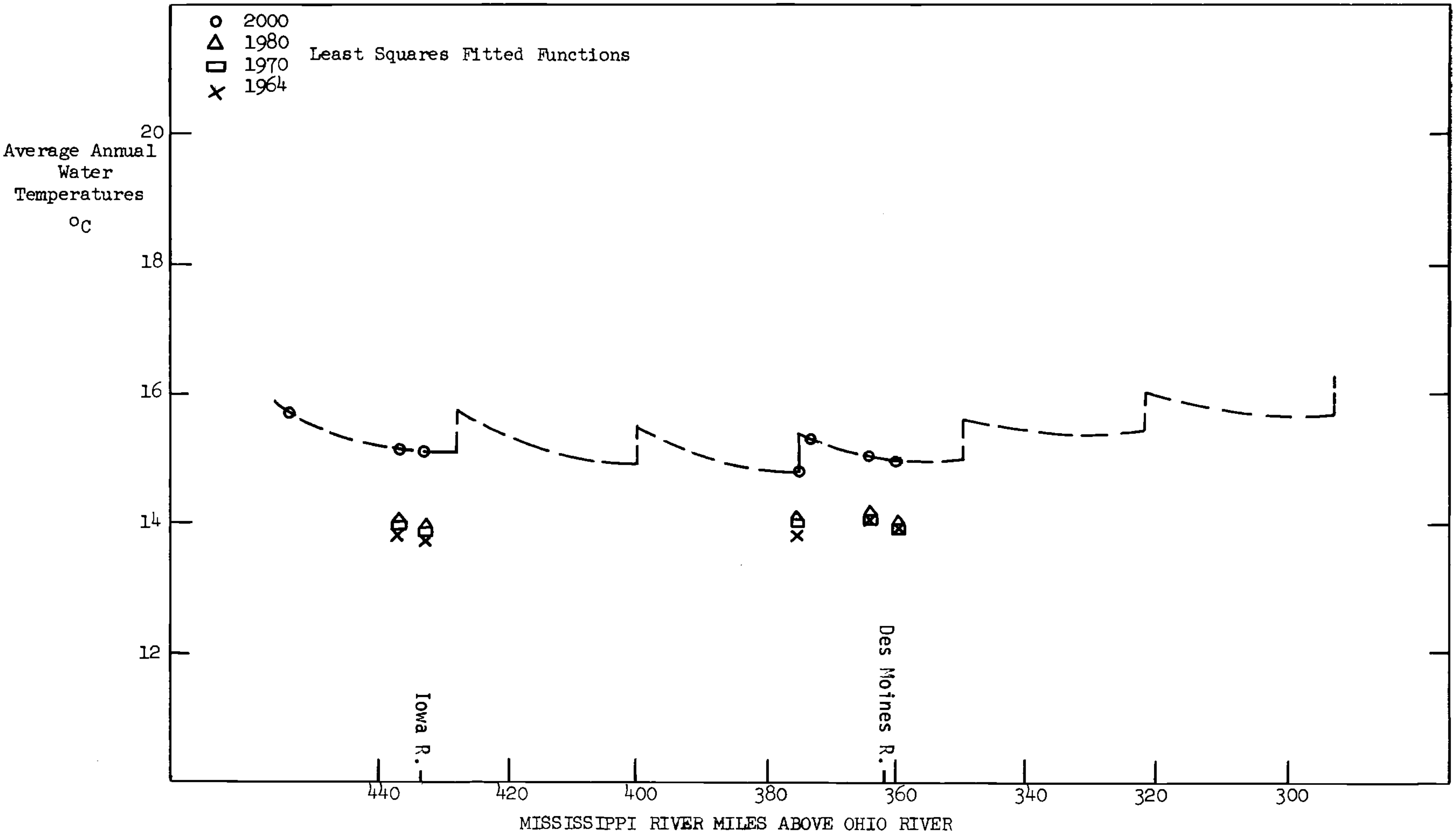


FIGURE 22d. Equilibration Profile, Mississippi River

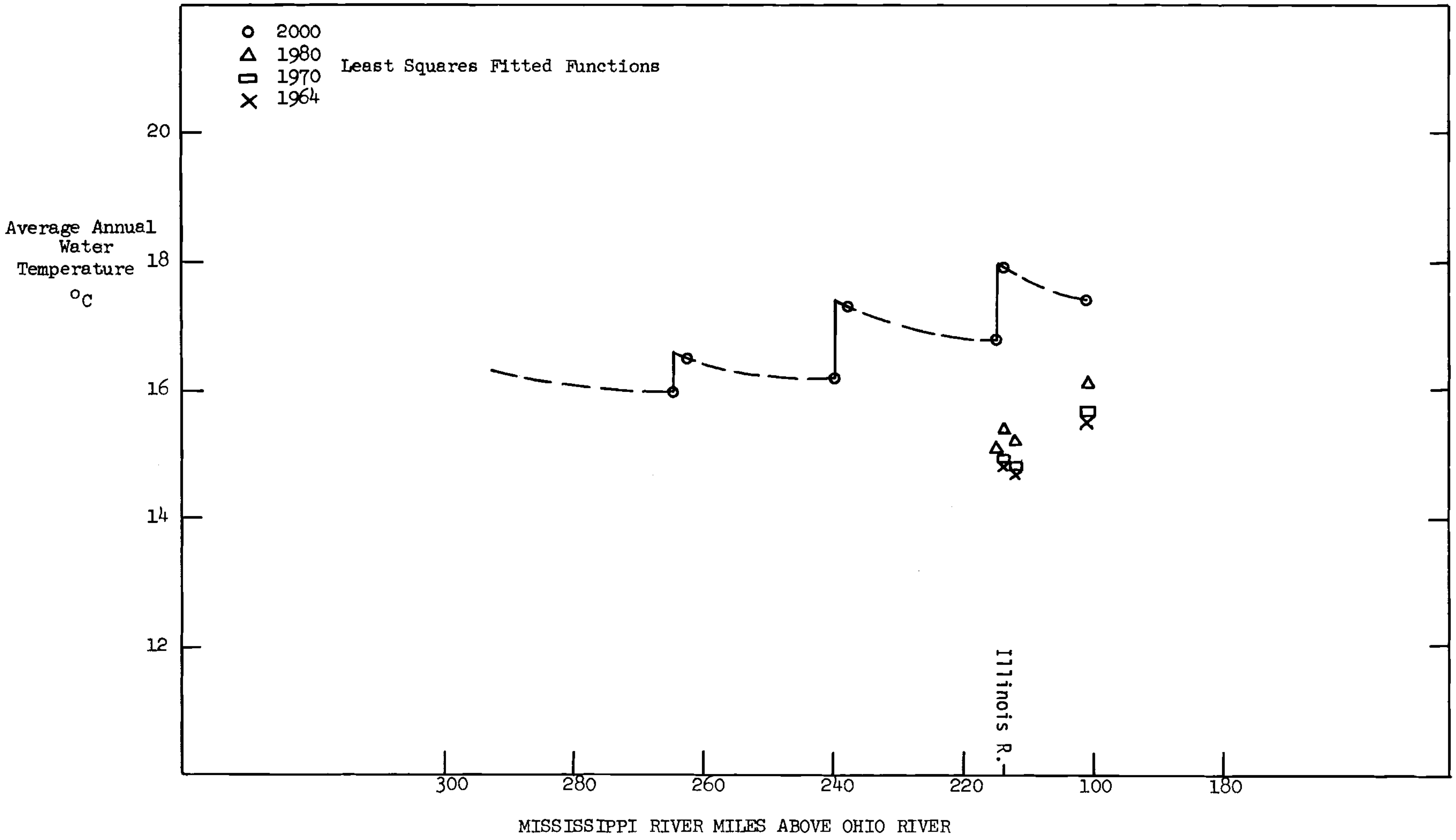


FIGURE 22e. Equilibration Profile, Mississippi River

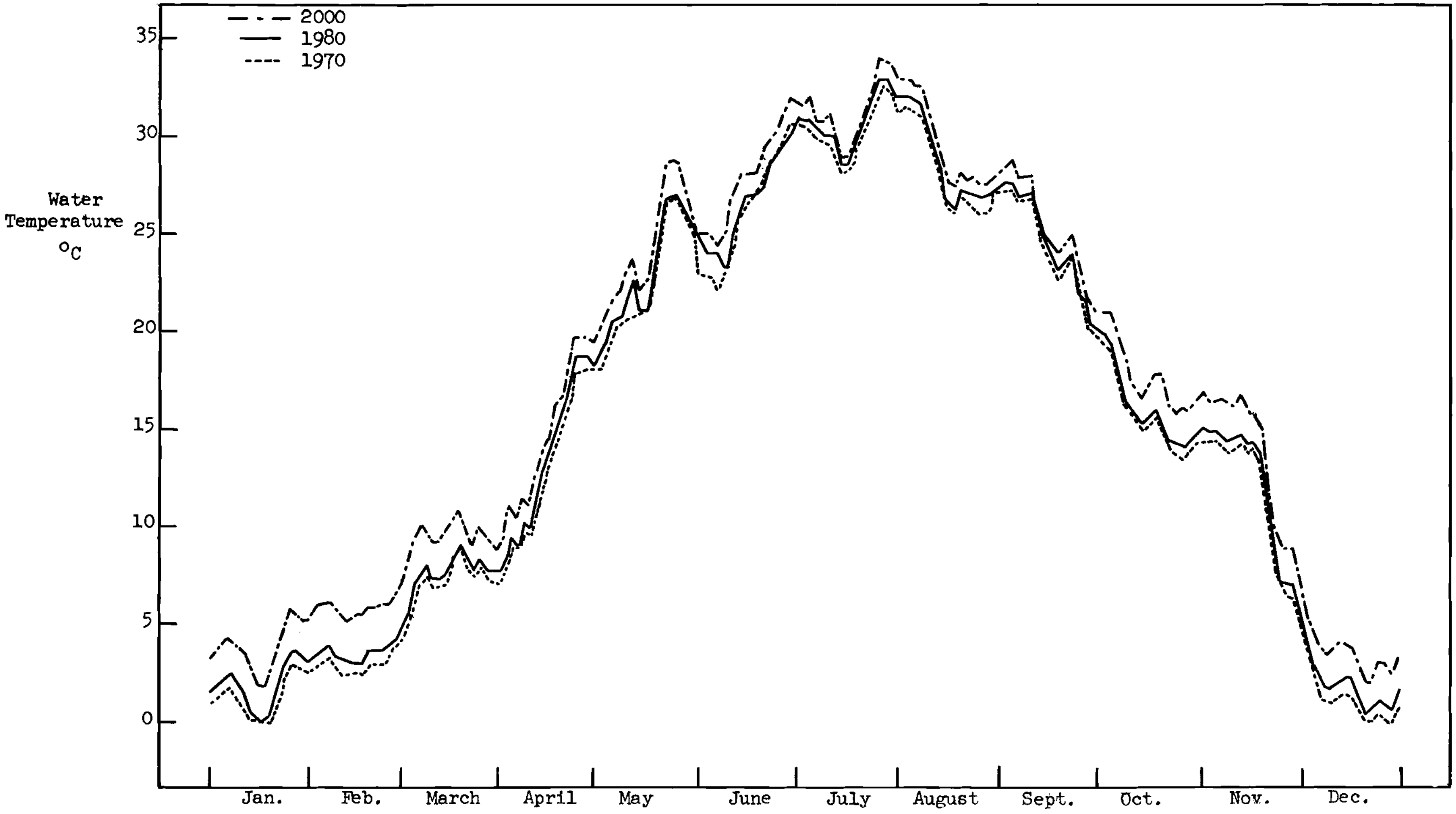


FIGURE 23. Computed Daily Water Temperatures at Alton, years 1970, 1980 and 2000

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APPENDIX

Summary of Least Squares Fitted Functions

$\bar{T}$ = T + B sin (Cd + D)

where $\bar{T}$ = Annual Average of Fitted Curve, C°

B = Amplitude of Variation, C°

C = Daily Progression $\left(\frac{2\pi}{366}\right)$

d = Number of Days

D = Radians from Year End for Peak Temperature Occurrence Date

= $366\left(1 - \frac{D}{2\pi}\right)$

Mississippi River - 1964

Location	$\overline{T}$ [°C]	B [°C]	D [rad]	Computed Annual Min [°C]	Computed Annual Max [°C]
Mile 852.9	12.2	13.7	3.8	0.0	25.9
844.1	12.9	14.3	3.9	0.0	27.2
839.3	13.0	14.2	3.9	0.0	27.2
811.4	13.5	14.7	4.0	0.0	28.2
800.0	12.8	14.2	3.9	0.0	27.0
763.6	12.8	14.2	3.9	0.0	27.0
632.9	13.2	14.5	4.0	0.0	27.7
511.8	13.3	14.6	4.0	0.0	27.9
509.8	13.3	14.6	4.0	0.0	27.9
482.0	13.4	14.7	4.0	0.0	28.1
437.0	13.8	15.0	4.1	0.0	28.8
375.0	14.0	15.1	4.1	0.0	29.1
364.0	14.0	15.1	4.1	0.0	29.1
214.0	14.8	14.9	4.4	0.0	29.7
201.0	15.5	14.8	4.4	0.7	30.3

Mississippi River - 1970

Location	$\overline{T}$ [°C]	B [°C]	D [rad]	Computed Annual Min [°C]	Computed Annual Max [°C]
Mile 852.9	12.6	13.9	3.9	0.0	26.5
844.1	13.3	14.3	4.0	0.0	27.6
839.3	13.2	14.3	4.0	0.0	27.5
811.4	13.6	14.7	4.1	0.0	28.3
800.0	12.9	14.2	4.0	0.0	27.1
763.6	12.8	14.2	3.9	0.0	27.0
632.9	13.2	14.5	4.0	0.0	27.7
511.8	13.3	14.6	4.0	0.0	27.9
509.8	13.7	14.9	4.1	0.0	28.6
482.0	13.7	14.9	4.1	0.0	28.6
437.0	13.9	15.0	4.1	0.0	28.9
375.0	14.0	15.1	4.1	0.0	29.1
364.0	14.0	15.1	4.1	0.0	29.1
214.0	14.9	14.8	4.4	0.1	29.7
201.0	15.6	14.8	4.4	0.8	30.4

Mississippi River - 1980

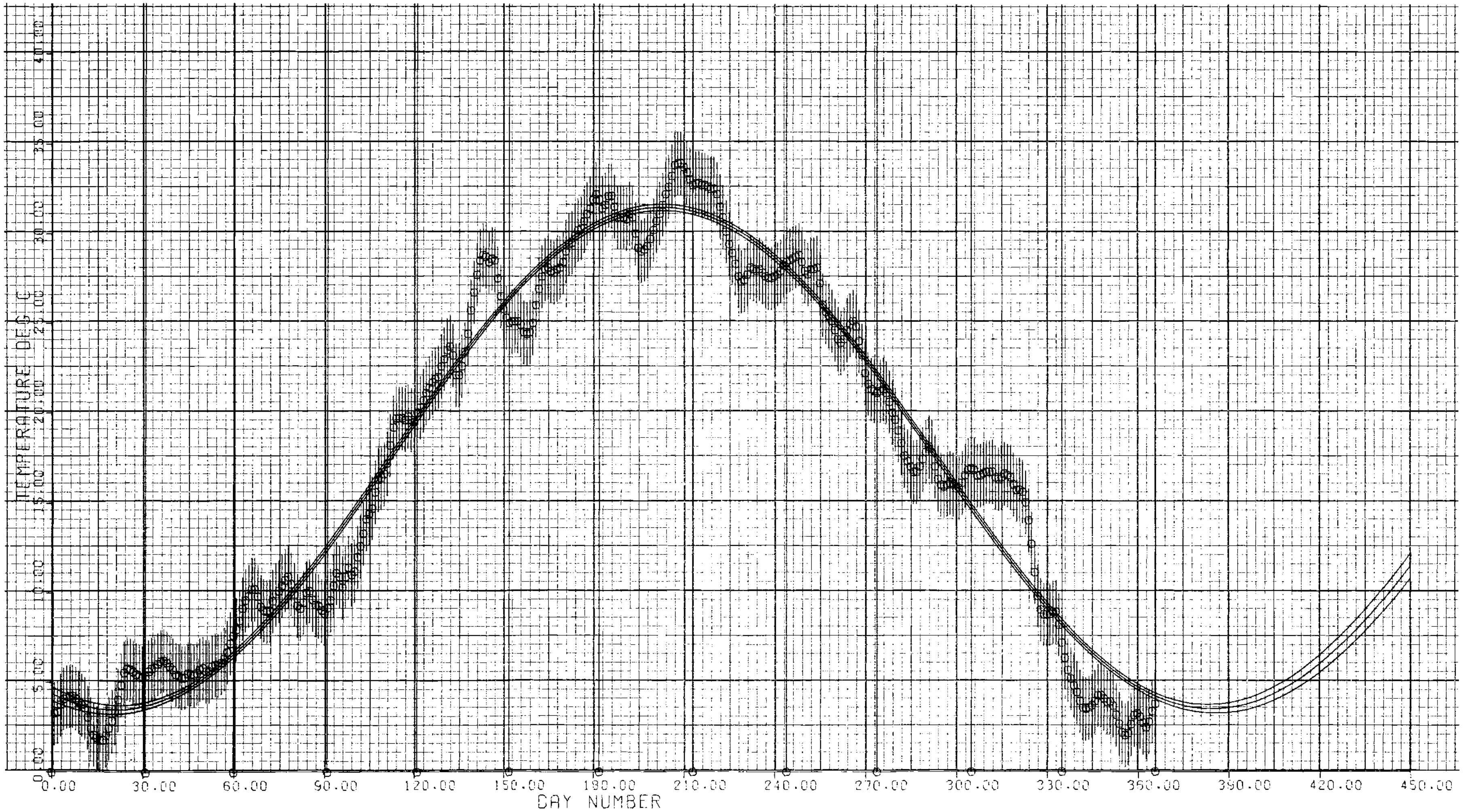
Location	$\overline{T}$ [°C]	B [°C]	D [rad]	Computed Annual Min [°C]	Computed Annual Max [°C]
Mile 852.9	12.5	13.8	3.8	0.0	26.3
844.1	13.0	14.3	3.9	0.0	27.3
839.3	13.2	14.4	4.0	0.0	27.6
811.4	13.5	14.6	4.0	0.0	28.1
800.0	12.8	14.1	3.9	0.0	26.9
798.0	13.8	14.5	4.1	0.0	28.3
763.6	13.3	14.4	4.0	0.0	27.7
632.9	13.3	14.6	4.0	0.0	27.9
511.8	13.4	14.7	4.0	0.0	28.1
509.8	14.0	15.1	4.1	0.0	29.1
482.0	13.8	14.9	4.1	0.0	28.7
437.0	14.0	15.0	4.1	0.0	29.0
375.0	14.1	15.1	4.1	0.0	29.2
364.0	14.1	15.1	4.1	0.0	29.2
215.0	15.1	14.8	4.3	0.3	29.9
214.0	15.4	14.7	4.3	0.7	30.1
201.0	16.1	14.6	4.4	1.5	31.2

Mississippi River - 2000

Location	$\bar{T}$ [°C]	B [°C]	D [rad]	Computed Annual Min [°C]	Computed Annual Max [°C]
Mile 926.0	11.4	12.6	3.8	0.0	24.0
924.0	13.8	12.2	3.8	1.6	26.0
900.0	12.8	13.4	4.0	0.0	26.2
898.0	17.5	12.9	4.0	4.6	30.4
865.0	13.9	14.2	4.3	0.0	28.1
852.9	15.2	13.8	4.4	1.4	29.0
844.1	14.6	14.1	4.4	0.5	28.7
839.3	14.7	14.4	4.5	0.3	29.1
837.0	21.2	12.2	4.0	9.0	33.4
811.4	15.5	14.0	4.5	1.5	29.5
658.0	14.4	14.8	4.5	0.0	29.2
656.0	15.4	14.7	4.5	0.7	30.1
632.9	14.2	14.7	4.5	0.0	28.9
609.5	14.3	15.1	4.4	0.0	29.4
607.5	14.9	15.1	4.4	0.0	30.0
580.0	13.9	15.2	4.5	0.0	29.1
578.0	15.6	14.9	4.4	0.7	30.5
545.2	14.1	15.0	4.5	0.0	29.1
511.8	14.2	15.1	4.5	0.0	29.3
509.8	15.5	15.0	4.5	0.5	30.5
482.0	15.8	14.8	4.5	1.0	30.6
456.0	14.9	15.1	4.5	0.0	30.0

Mississippi River - 2000 (Continued)

Location	$\overline{T}$ [°C]	B [°C]	D [rad]	Computed Annual Min [°C]	Computed Annual Max [°C]
Mile 454.0	15.7	15.0	4.4	0.7	30.7
437.0	15.2	15.1	4.5	0.1	30.3
375.0	14.8	15.2	4.4	0.0	30.0
373.3	15.3	15.2	4.4	0.1	30.5
364.0	15.0	15.3	4.4	0.0	30.3
265.0	16.0	14.6	4.4	1.4	30.6
263.0	16.5	14.4	4.4	2.1	30.9
240.0	16.2	14.5	4.4	4.4	30.7
238.0	17.3	14.2	4.3	3.1	31.5
215.0	16.8	14.1	4.4	2.7	30.9
214.0	17.9	13.9	4.3	4.0	31.8
201.0	17.5	14.0	4.4	3.5	31.5



$$T = 17.5 + 14.0 \sin(0.173d + 4.4)$$

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