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HEAT ASSIMILATIVE CAPACITY OF THE SANGAMON RIVER

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HEAT ASSIMILATIVE CAPACITY OF THE SANGAMON RIVER

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ABSTRACT

HEAT ASSIMILATIVE CAPACITY OF THE SANGAMON RIVER

A standard procedure for determining the distribution and variation of the heat assimilative capacity of a river has been developed. Hydraulic geometry equations for the Sangamon River Basin are used to provide the necessary hydraulic information. This study indicates that the total heat assimilative capacity of a river depends on the location of power plants, residual temperature, flow frequency, and seasonal variation of water temperature and wind speed.

Water temperature data from 18 gaging stations in the Sangamon River Basin and wind speed data from 5 weather stations in or near the basin are used to determine the surface transfer coefficient for excess heat along the Sangamon River. This coefficient can be approximated by four equations for different ranges of wind speed. An analysis of the cost-capacity relationships for 29 power plants indicates that the cost per kilowatt of power output decreases with increasing power plant capacity.

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KEY WORDS: Costs, excess temperature, heat capacity, heat transfer, hydraulic geometry, power plants, rivers, water temperature.

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INTRODUCTION

A survey made by the Federal Power Commission (1971) indicates that the electric energy consumption for Illinois, as well as the United States, will double every ten years. On the average, for each kilowatt-hour of electric energy produced in a fossil fuel power plant, two-thirds of the heat produced is waste that must be dissipated. The simplest method of disposing this waste heat along a river is to discharge it directly to the water and let natural processes bring the water back to its natural temperature. This report is a pilot study to develop a standard procedure for determining the distribution and variation of the heat assimilative capacity of the Sangamon River.

The total heat assimilative capacity of a river depends on its climatic and hydraulic conditions as well as locations of power plants and allowable excess temperature. For a given flow frequency and allowable excess temperature, the locations of power plants along the Sangamon River and their allowable capacities can be determined. Hydraulic and water temperature data collected by the U.S. Geological Survey at 18 stream gaging stations and wind speed measurements by the U.S. Weather Bureau at 5 weather stations are used in this study.

Acknowledgments

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BACKGROUND

Excess Temperature Decay

The heat assimilative capacity H of a stream at a given location for a given water discharge Q and an allowable excess temperature T_{eo} above the natural water temperature is

$$H \text{ (Btu/hr)} = T_{eo} \text{ (°F)} \times Q \text{ (cfs)} \times 62.4 \text{ (lb/ft}^3\text{)} \times 3600 \text{ (sec/hr)} \times 1 \text{ (Btu/lb°F)} = 224640\, T_{eo}\, Q \quad (1)$$

If the in-plant heat loss is assumed to be 5 percent, and the thermal efficiency is 33 percent, then 6410 Btu of waste heat is discharged to water for each kilowatt-hour output from a fossil fuel power plant (Federal Water Pollution Control Administration, 1968). If there is no cooling pond nor cooling tower, the allowable power plant capacity KW is

$$KW = H\text{(Btu/hr)}/6410 \text{ (Btu/kw-hr)} = 35\, T_{eo} Q \quad (2)$$

The maximum allowable excess temperature T_{eo} set by the Environmental Protection Agency of Illinois (1972) is 5°F, provided that the water temperature will not exceed 90°F after receiving the waste heat.

The heat disposal problem in a stream can be divided into two zones (Edinger, 1969): 1) the initial mixing, and 2) the atmospheric cooling. The length of the mixing zone is relatively short and can be neglected. The rate of water temperature decay downstream from a power plant will determine the location and capacity of the next power plant. The traditional approach for the prediction of temperature decay after initial mixing is to determine the equilibrium temperature by an exponential decay function (Edinger and Geyer, 1965). The equilibrium temperature is a complex function of climatic factors. The COLHEAT model (Hanford Engineering Development Laboratory, 1972; Peterson et al, 1973) is based on this equilibrium temperature concept. Recent studies by Jobson (1973) and Yotsukura et al. (1973) indicate that the excess temperature caused by man's interference with natural conditions is a better parameter than the equilibrium temperature for determining the temperature decay.

The excess temperature T_e at a distance X downstream from the point of initial introduction of allowable excess temperature T_{eo} can be expressed by

$$T_e = T_{eo} \exp - (DX/UZ) \tag{3}$$

where D is the surface transfer coefficient for excess heat, U is the average flow velocity, and Z is the average water depth. Theoretically, the transfer coefficient D should be related to back radiation, evaporation, conduction, and advection by evaporated water. Yet the calculated result by Jobson (1973) indicates that the transfer coefficient is not sensitive to changes in atmospheric conditions. Jobson shows that the transfer coefficient is mainly a function of wind speed and natural water temperature. The advantage of using the new excess temperature approach rather than the traditional equilibrium temperature approach was discussed in detail by Paily et al. (1974) and the new approach is used in this study.

Hydraulic Geometry

The study of hydraulic geometry of Illinois streams by Stall and Fok (1968) showed a consistent pattern within a river basin between hydraulic geometry, flow frequency F, and drainage area A_d. The hydraulic geometry equations were further verified by Stall and Yang (1970) for 12 river basins in the United States. The hydraulic geometry includes water discharge Q in cubic feet per second, average velocity U in feet per second, average depth Z in feet, channel width W in feet, and channel cross-sectional area A in square feet. The discharge, velocity, and depth for the Sangamon River Basin in Illinois can be expressed by equations 4, 5, and 6, respectively (Stall and Yang, 1970).

$$\ln Q = 0.30 - 5.39\ F + 1.1 \ln\ A_d \qquad (4)$$

$$\ln U = - 0.89 - 1.18\ F + 0.23 \ln A_d \qquad (5)$$

$$\ln Z = - 0.26 - 2.69\ F + 0.33 \ln A_d \qquad (6)$$

The allowable power plant capacity KW at a distance X down stream from the point of initial introduction of excess heat can be expressed as a function of flow frequency, drainage area, and allowable excess temperature with the use of equations 2 through 6, after the surface transfer coefficient for excess heat D has been determined.

DATA

Water Temperature

Figure 1 shows the 18 stream gaging stations in the Sangamon River Basin, identified by their U.S. Geological Survey gaging station numbers. Water temperature at these stations is measured by the U.S. Geological Survey whenever a discharge measurement is made. These unpublished temperature data can be found at the U.S. Geological Survey District Office in Champaign, Illinois. The monthly low, mean, and high water temperatures at each gaging station are summarized in table 1. The variations of water temperature at these gaging stations are shown in the appendix. The monthly average water temperature for 7 stations along or near the main stem of the Sangamon River are plotted on figure 2. These data are fitted by smooth curves to show the variation of monthly mean water temperature as a function of the location of stations along the main stem of the Sangamon River.

Wind Speed

The locations of 5 weather stations in or near the Sangamon River Basin are shown in figure 1. Wind speeds at these stations are measured daily by the U.S. Weather Bureau and results are published annually by the U.S. Department of Commerce. These data are measured at different heights above ground level. In order to compare them it is necessary to find out their corresponding values at a common height above ground level. This can be done by the use of Nordenson's (1962) equation

$$U_{a1}/U_{a2} = (Y_1/Y_2)^{0.3} \qquad (7)$$

where U_{a1} is the wind speed in miles per hour at pan anemometer height, U_{a2} is the wind speed in miles per hour at weather

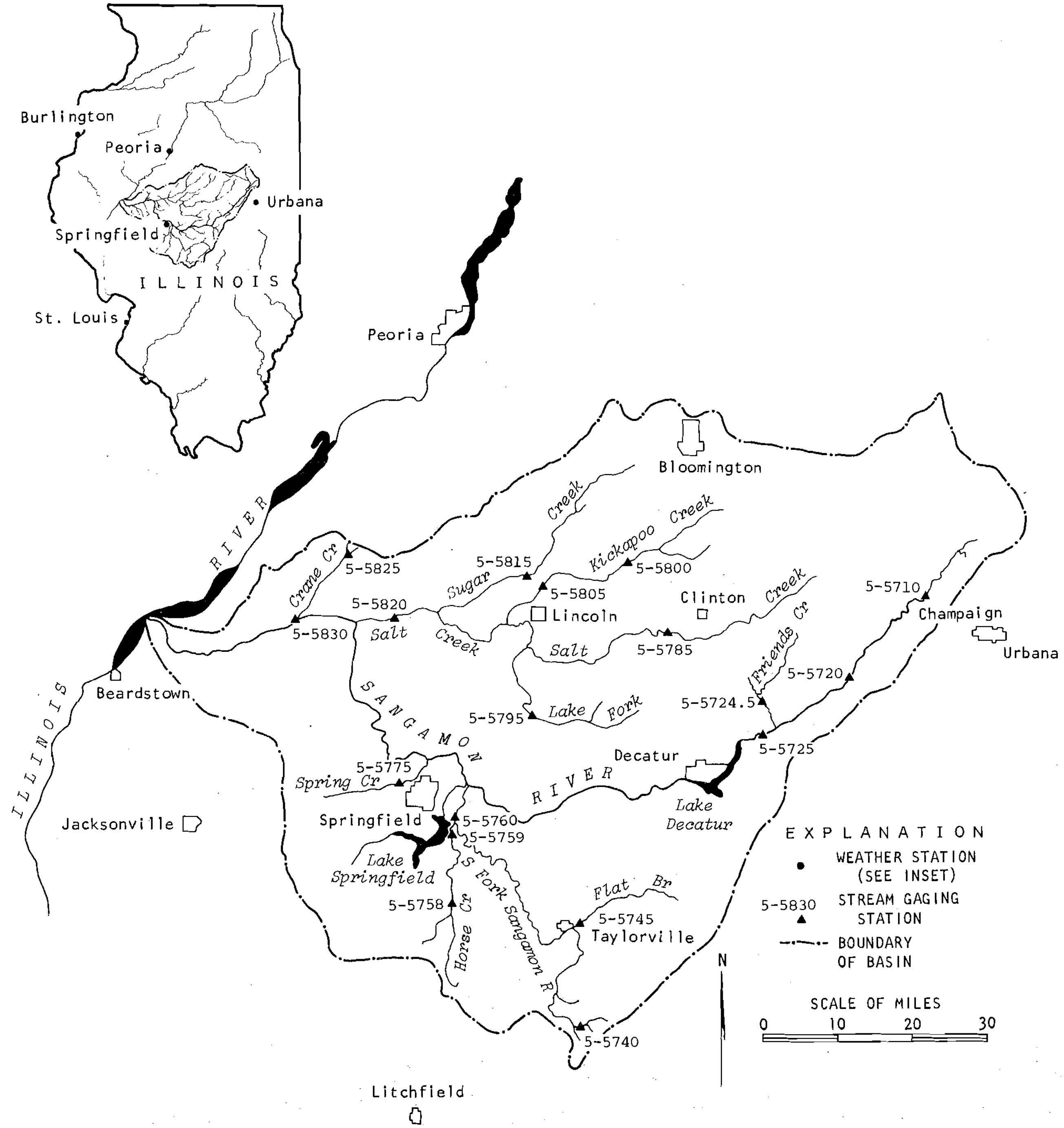

Figure 1. Location of stream gaging stations in the Sangamon River Basin

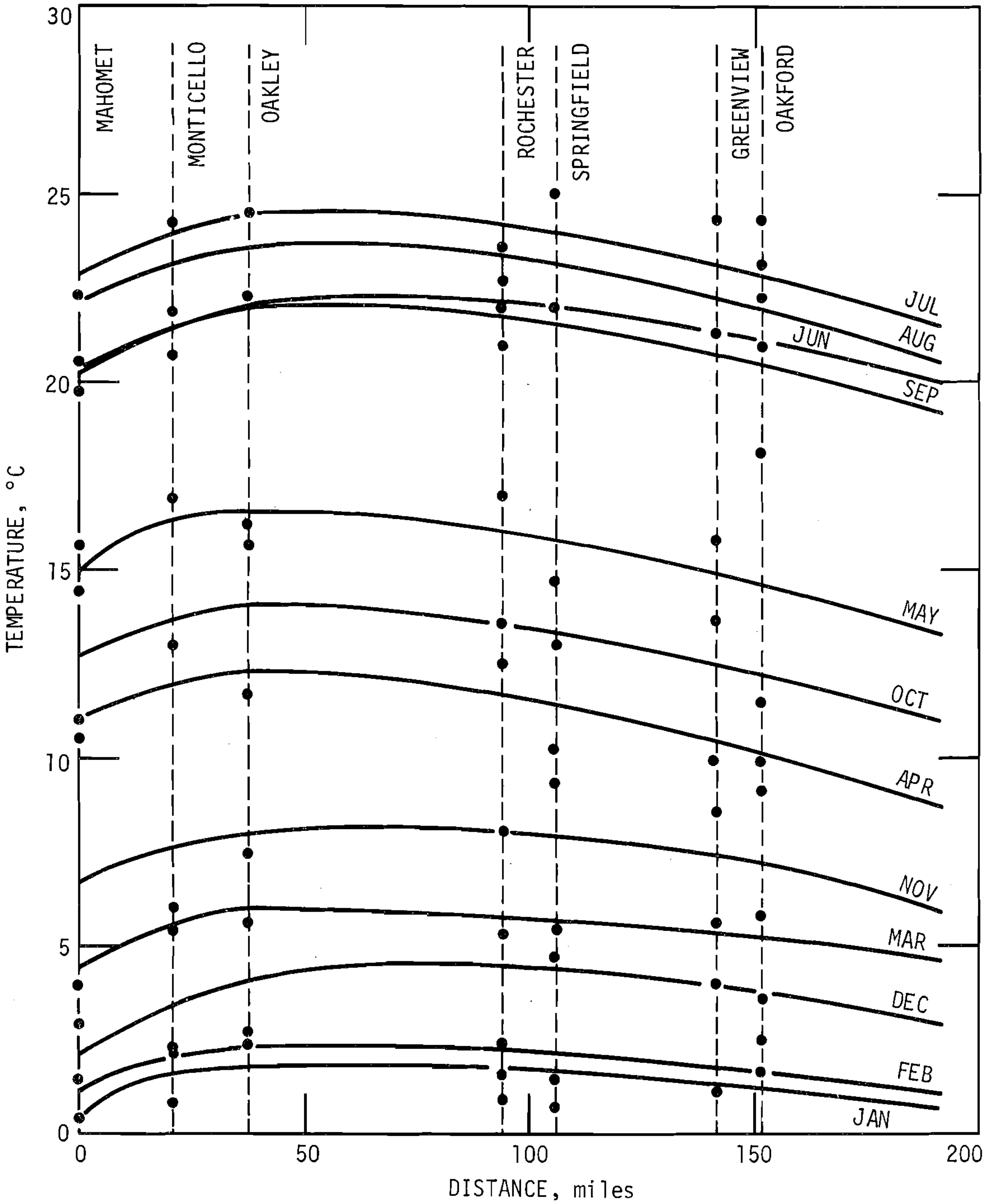

Figure 2. Variation of monthly mean water temperature at stations along the main stem of the Sangamon River.

Table 1. Water Temperatures (in °C) at stream gaging stations in the Sangamon River Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5-5710 Sangamon River at Mahomet (9 years 1965-1973)												
low	0	0	2.0	6.0	11.0	14.0	18.0	20.0	14.0	9.0	3.0	0
mean	0.4	1.4	3.9	11.0	14.4	20.6	22.3	22.2	19.7	15.6	10.5	2.9
high	2.0	8.0	8.0	17.0	18.0	28.0	27.0	24.0	24.0	17.0	13.0	8.0
5-5720 Sangamon River at Monticello (12 years 1959-1961 1965-1973)												
low	0	0	0	1.0	11.0	18.0	20.0	10.0	15.0	3.0	0	0
mean	0.8	2.1	6.0	13.0	16.9	20.7	24.2	21.6	21.9	12.1	5.4	2.2
high	3.0	5.0	14.0	18.0	25.0	26.0	32.0	27.0	31.0	17.0	14.0	8.0
5-5724.5 Friends Creek at Argenta (6 years 1968-1973)												
low	0	0	2.0	6.0	13.0	16.0	18.0	20.0	18.0	8.0	5.0	0
mean	0.3	1.4	5.6	9.2	14.2	19.8	22.2	23.8	20.2	14.5	7.0	4.6
high	1.0	5.0	10.0	13.0	16.0	24.0	26.0	28.0	22.0	18.0	10.0	9.0
5-5725 Sangamon River near Oakley (5 years 1969-1973)												
low	2.0	0	2.0	7.0	12.0	18.0	20.0	23.0	22.0	11.0	6.0	1.0
mean	2.7	2.3	5.6	11.7	15.6	22.1	22.3	24.5	24.5	16.2	7.4	2.7
high	4.0	7.0	10.0	14.0	19.0	26.0	26.0	26.0	27.0	19.0	9.0	4.0
5-5740 South Fork Sangamon River near Nokomis (7 years 1965-1966 1968-1972)												
low	0	0	1.0	10.0	15.0	19.0	18.0	20.0	16.0	12.0	4.0	0
mean	1.3	1.7	7.0	13.0	19.8	24.4	25.4	24.3	21.7	15.4	7.3	2.6
high	6.0	5.0	17.0	18.0	28.0	29.0	32.0	27.0	25.0	21.0	9.0	6.0
5-5745 Flat Branch near Taylorville (9 years 1965-1973)												
low	0	0	2.0	7.0	9.0	20.0	22.0	20.0	16.0	10.0	3.0	0
mean	1.5	1.9	6.9	11.2	16.8	21.8	24.1	23.3	20.0	15.6	7.5	4.8
high	4.0	5.0	15.0	14.0	21.0	24.0	28.0	27.0	23.0	19.0	11.0	15.0
5-5758 Horse Creek at Pawnee (6 years 1969-1973)												
low	0	0.7	3.0	9.0	13.0	20.0	21.0	20.0	17.0	13.0	5.0	0
mean	1.2	1.5	5.3	11.2	17.4	21.0	24.1	26.7	21.1	14.0	8.2	2.7
high	3.0	4.0	10.0	13.0	21.0	23.0	27.0	34.0	25.0	15.0	10.0	6.0
5-5759 Horse Creek near Rochester (4 years 1968-1971)												
low	0	1.0	3.0	7.0	14.0	18.0	21.0	19.0	14.0	8.0	8.0	2.0
mean	0.4	1.3	4.8	12.0	20.7	21.0	23.4	22.3	19.8	13.7	8.3	2.0
high	1.0	2.0	7.0	16.0	27.0	23.0	26.0	26.0	25.0	17.0	9.0	2.0
5-5760 South Fork Sangamon River near Rochester (9 years 1965-1973)												
low	0	0	2.0	7.0	13.0	17.0	20.0	21.0	16.0	9.0	6.0	1.0
mean	0.9	1.6	5.3	12.5	17.0	22.0	23.6	22.7	21.0	13.6	8.0	2.4
high	2.0	4.0	8.0	17.0	22.0	24.0	32.0	24.0	25.0	20.0	10.0	3.0

Table 1 (continued)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5-5775 Spring Creek at Springfield (7 years 1965-1966 & 1969-1973)												
low	0	0	3.0	4.0	11.0	20.0	21.0	23.0	20.0	11.0	4.0	1.0
mean	0.7	1.4	5.4	10.2	14.7	22.0	25.0	25.1	22.0	13.0	9.3	4.7
high	1.0	5.0	7.0	16.0	18.0	24.0	32.0	31.0	28.0	17.0	14.0	10.0
5-5785 Salt Creek near Rowell (9 years 1965-1973)												
low	0	0	1.0	5.0	13.0	19.0	20.0	20.0	17.0	9.0	2.0	1.0
mean	0.8	1.3	4.7	10.6	17.3	22.3	23.4	23.9	19.9	14.1	7.0	2.5
high	4.0	3.0	10.0	18.0	21.0	27.0	29.0	26.0	25.0	18.0	14.0	10.0
5-5795 Lake Fork near Cornland (5 years 1965-1966 & 1969-1971)												
low	0	0	2.0	6.0	11.0	17.0	20.0	18.0	19.0	12.0	5.0	1.0
mean	0.5	2.1	5.4	10.1	16.2	19.8	24.0	23.7	22.1	14.9	10.3	4.1
high	1.0	4.0	8.0	12.0	20.0	24.0	32.0	32.0	24.0	18.0	16.0	14.0
5-5800 Kickapoo Creek at Waynesville (5 years 1969-1973)												
low	0	0	1	2	11.0	19.0	18.0	20.0	18.0	11.0	2.0	0
mean	1.5	0.9	4.3	8.3	13.3	20.7	23.0	21.8	21.3	15.0	4.7	4.5
high	6.0	2.0	9.0	15.0	17.0	24.0	30.0	23.0	24.0	17.0	8.0	11.0
5-5805 00 Kickapoo Creek near Lincoln (4 years 1966 & 1969-1971)												
low	0	0	2.0	5.0	11.0	21.0	21.0	20.0	20.0	12.0	2.0	1.0
mean	2.0	1.5	7.8	8.0	14.8	22.0	24.2	21.3	21.8	15.0	4.8	3.8
high	6.0	3.0	14.0	15.0	18.0	24.0	28.0	23.0	25.0	18.0	7.0	11.0
5-5815 00 Sugar Creek near Hartsburg (3 years 1969-1971)												
low	0	0	1.0	4.0	12.0	22.0	23.0	20.0	24.0	9.0	4.0	1.0
mean	2.7	1.3	5.4	8.5	16.0	23.5	25.3	23.3	25.7	14.3	7.3	5.6
high	7.0	2.0	12.0	16.0	19.0	26.0	29.0	26.0	28.0	18.0	10.0	11.0
5-5820 Salt Creek near Greenview (7 years 1965-1966 & 1969-1973)												
low	0	0	1.0	5.0	13.0	19.0	22.0	20.0	19.0	10.0	5.0	0.0
mean	1.1	1.1	5.6	8.5	15.8	21.3	24.3	22.3	21.3	13.7	9.9	4.0
high	3.0	3.0	10.0	15.0	20.0	24.0	28.0	24.0	27.0	17.0	14.0	11.0
5-5825 Crane Creek near Easton (10 years 1962-1966 & 1969-1973)												
low	0	0.6	3.0	6.0	12.0	18.0	20.0	18.0	7.0	11.0	5.0	2.0
mean	3.3	4.1	7.4	11.5	17.5	21.5	22.2	21.8	18.3	16.4	8.8	6.0
high	7.0	6.0	13.0	18.0	23.0	29.0	26.0	24.0	25.0	22.0	15.0	15.0
5-5830 Sangamon River near Oakford (12 years 1957-1961 & 1965-1966 & 1969-1973)												
low	0	0	1.0	6.0	14.0	21.0	20.0	21.0	17.0	10.0	4.0	0
mean	2.5	1.6	5.8	11.5	18.1	22.3	24.3	23.2	21.0	14.6	9.1	3.6
high	8.0	5.0	10.0	18.0	21.0	24.0	32.0	26.0	25.0	18.0	16.0	10.0

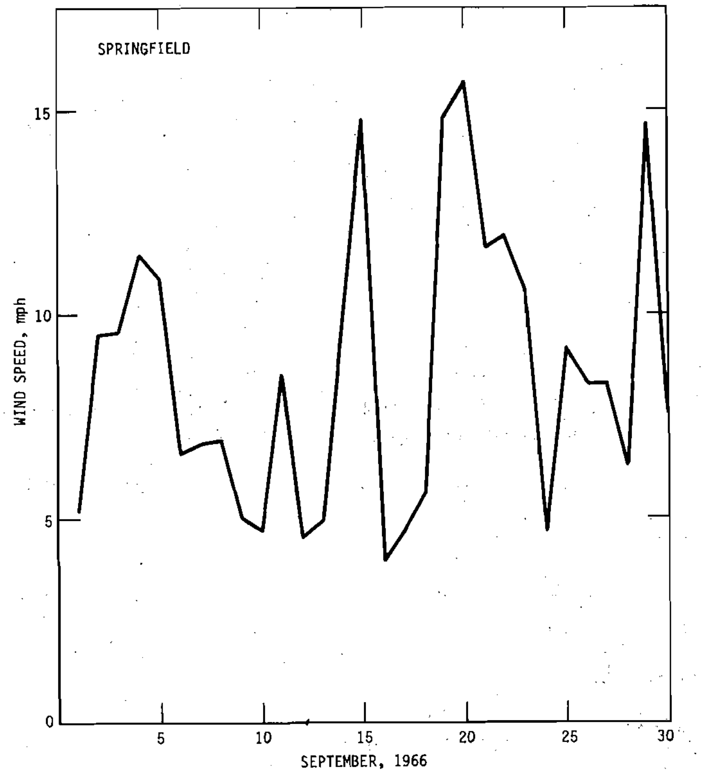

Figure 3. Variation of wind speed

station anemometer, Y_1 is the height of pan anemometer (2 feet), and Y_2 is the height of weather station anemometer. Figure 3 shows an example of the variation of daily wind speed at Springfield in September 1966. The monthly average wind speed at 5 weather stations and their corresponding speeds at 6 feet above ground level are summarized in table 2.

Since wind speed data for stream gaging stations are not available, their values were estimated by linear interpolation of the data shown in table 2. These results were further used to determine the variation of monthly average wind speed along the main stem of the Sangamon River (figure 4).

ANALYSES

Transfer Coefficient

A surface transfer coefficient for excess heat, D, is defined (Jobson, 1973) as

$$D = D_b + D_e + D_h + D_w \qquad (8)$$

Table 2. Wind Speed (in mph) Observed at Various Locations in and near the Sangamon River Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Peoria, Il (10 years 1964-1973) anemometer height = 20 feet												
average	11.2	11.1	12.0	12.0	10.1	8.9	7.6	7.6	8.4	9.3	10.3	10.9
6 feet	8.0	7.9	8.6	8.6	7.2	6.4	5.4	5.4	6.0	6.7	7.4	7.8
Burlington, Ia (11 years 1963-1973) anemometer height = 33 feet												
average	11.7	11.6	12.2	12.2	10.4	9.3	8.7	7.7	8.6	9.6	10.5	10.9
6 feet	7.2	7.1	7.5	7.5	6.4	5.7	5.3	4.7	5.3	5.9	6.4	6.7
Springfield, Il (10 years 1964-1973) anemometer height = 20 feet												
average	12.9	12.5	13.5	13.2	11.6	10.1	8.4	8.2	9.1	10.4	11.6	12.4
6 feet	9.2	9.0	9.7	9.5	8.3	7.3	6.0	5.9	6.5	7.4	8.3	8.9
Urbana, Il (13 years 1961-1973) anemometer height = 55 feet												
average	8.7	8.7	9.2	9.1	7.7	6.4	5.2	5.2	5.7	6.5	7.8	8.2
6 feet	4.6	4.6	4.9	4.8	4.1	3.4	2.7	2.7	3.0	3.4	4.1	4.3
St. Louis, Mo (10 years 1964-1973) anemometer height = 20 feet												
average	10.4	10.6	11.5	11.3	9.3	9.0	8.1	8.0	8.4	9.2	10.0	10.4
6 feet	7.4	7.6	8.2	8.1	6.7	6.4	5.8	5.7	6.0	6.6	7.2	7.4

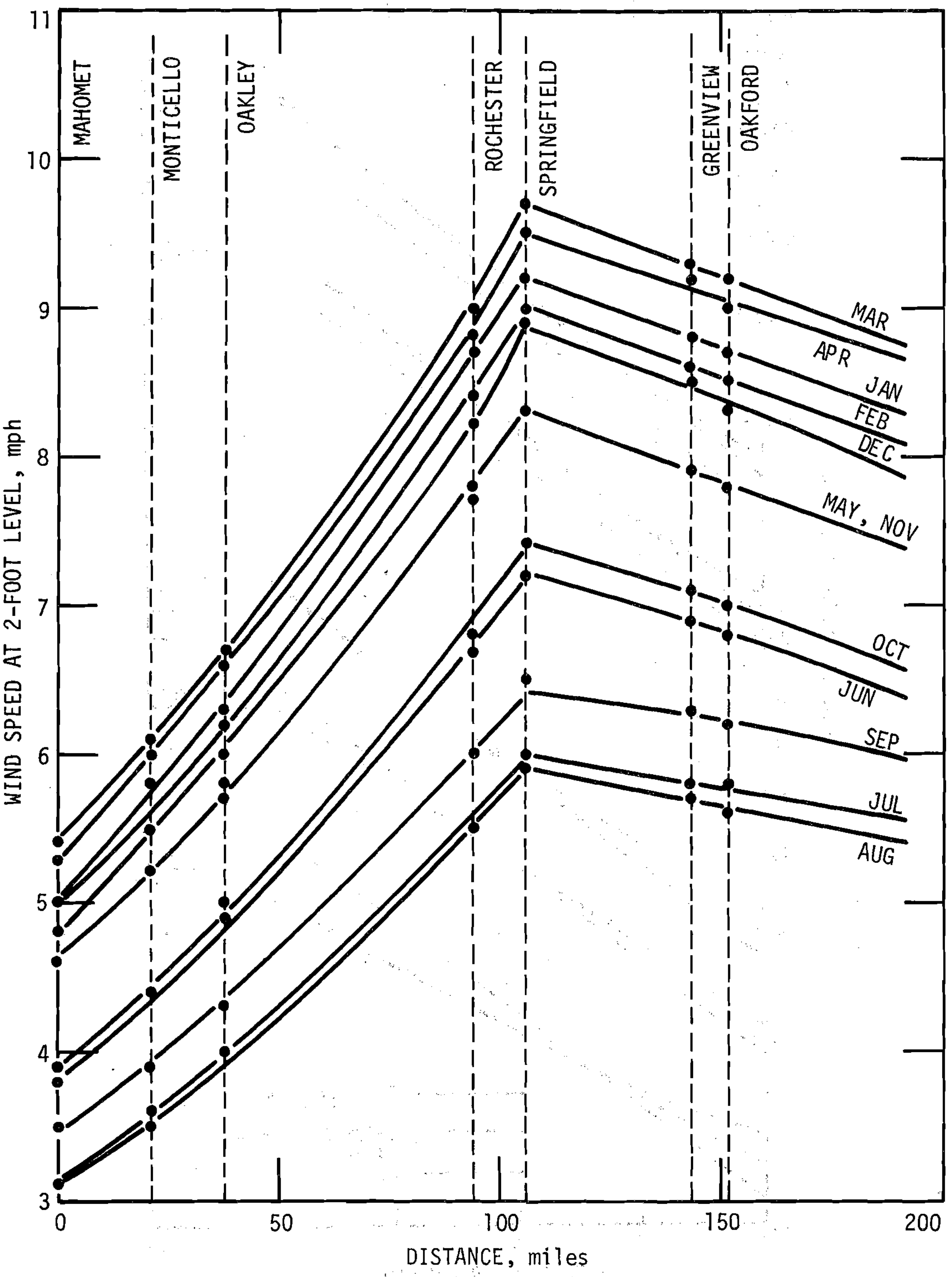

Figure 4. Average monthly wind speed along the main stem of the Sangamon River

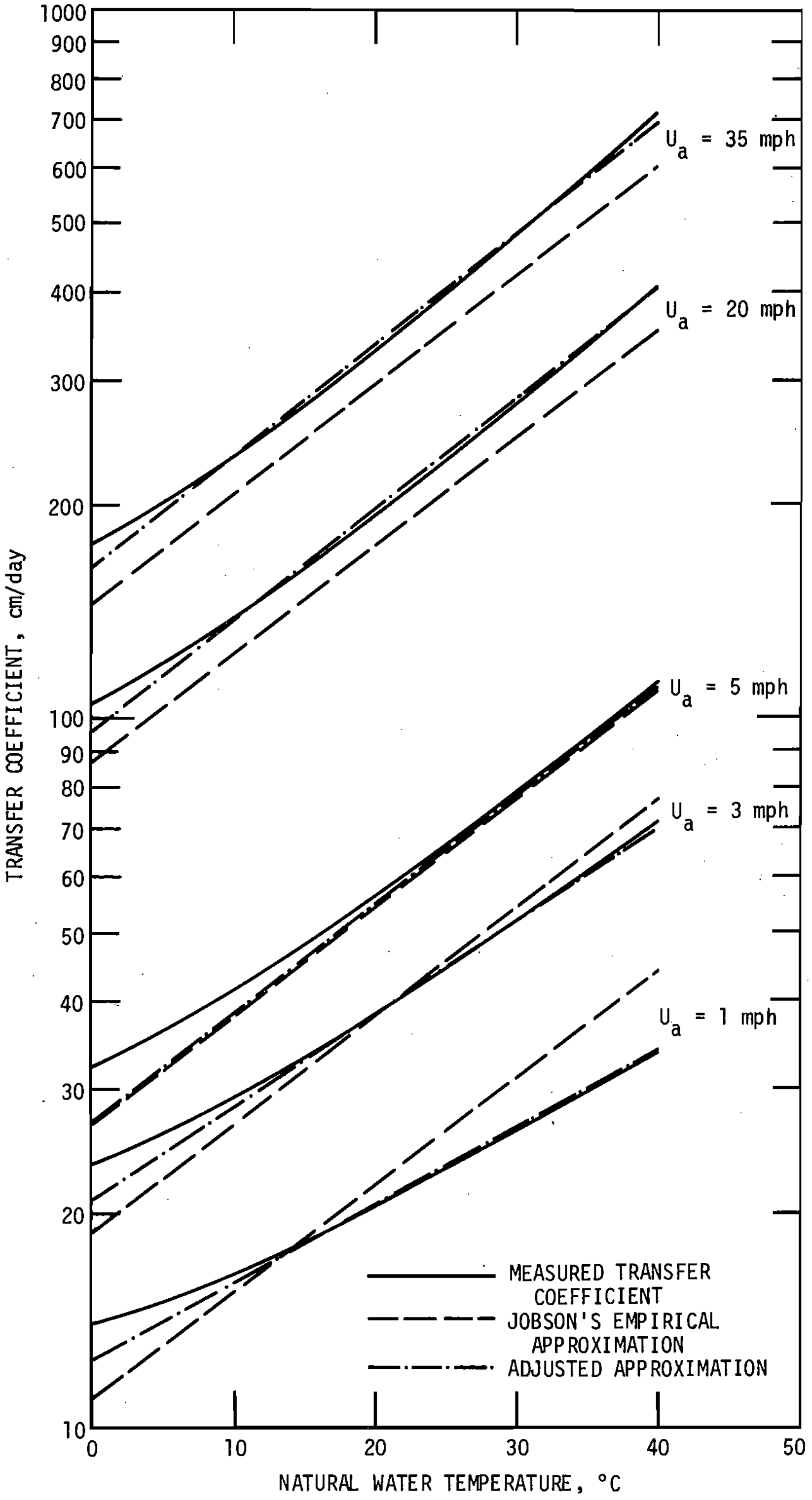

Figure 5. Comparison of transfer coefficients for excess heat

where D_b is the surface transfer coefficient for excess heat which results from back radiation, D_e is that coefficient resulting from evaporation, D_h is that coefficient resulting from conduction, and D_w is that coefficient resulting from advection by evaporated water. Jobson's calculated result indicates that the transfer coefficient is not sensitive to changes in atmospheric conditions. He developed an empirical equation for the transfer coefficient as a function of wind speed U_a and natural water temperature T_o

$$D = (7 + 4\ U_a) \exp (0.035\ T_o) \qquad (9)$$

A comparison between equation 9 and the measured transfer coefficient as shown in figure 5 indicates that further improvement of equation 9 is needed.

In order to minimize the deviation of the calculated results from the measured transfer coefficient, regression analyses were made for different ranges of wind speed and natural water temperature. It was found that the transfer coefficient in centimeters per day can be approximated better by the following four equations

$$D = (8 + 4.5\ U_a) \exp (0.025\ T_o);\ 0 \leq U_a \leq 2 \qquad (10)$$

$$D = (4.5 + 5.5\ U_a) \exp (0.030\ T_o);\ 2 < U_a \leq 4 \qquad (11)$$

$$D = (7 + 4\ U_a) \exp (0.035\ T_o);\ 4 < U_a \leq 10 \qquad (12)$$

$$D = (6 + 4.5\ U_a) \exp (0.036\ T_o);\ 10 < U_a \leq 35 \qquad (13)$$

where wind speed is measured in miles per hour and natural water temperature T_o in degrees Celsius. Equations 10 through 13 provide better approximations of the transfer coefficient than equation 9. Equations 10 through 13 are used in this report to calculate the transfer coefficient for excess heat.

Excess Temperature Decay

At any point along the main stem of the Sangamon River, its drainage area A_d in square miles and distance X in miles downstream from Mahomet can be measured from topographic maps. The relationship between A_d and X is shown in figure 6. It can be approximated by the following three equations

$$A_d = 342.5 + 11.4\ X\ ;\ 0 \leq X \leq 94.7 \qquad (14)$$

$$A_d = -766.2 + 51.6\ X - 0.172\ X^2;\ 94.7 < X \leq 143.5 \qquad (15)$$

$$A_d = 3659.4 + 9.64\ X;\ 143.5 < X \leq 177.5 \qquad (16)$$

These equations also allow the drainage area at a distance X

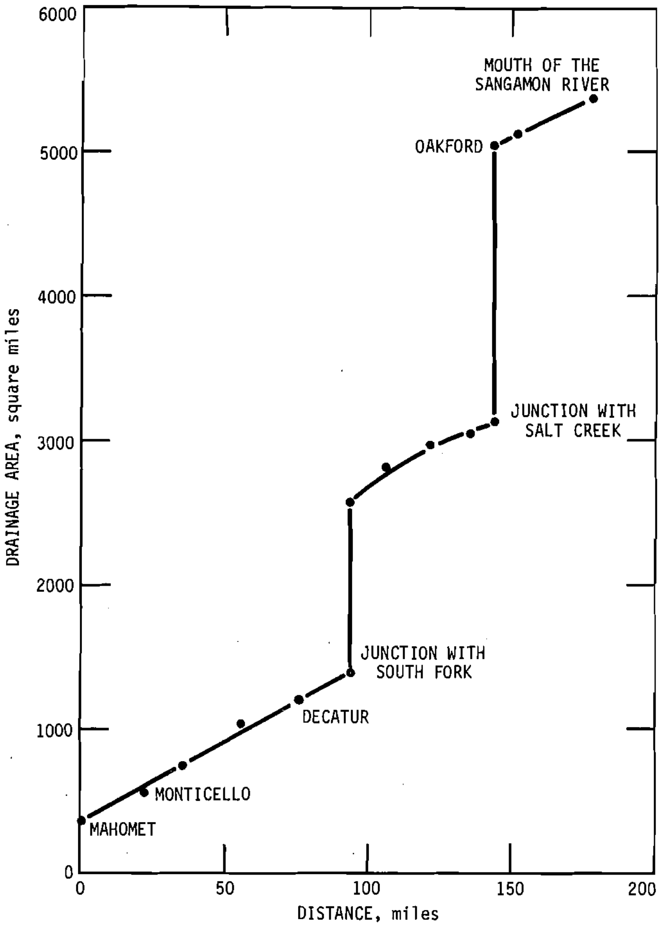

Figure 6. Relationship between drainage area and distance downstream from Mahomet

downstream from Mahomet to be calculated. The water discharge Q, average flow velocity U, and water depth Z at this point can then be calculated by equations 4, 5, and 6 for a given flow frequency. The natural water temperature T_o and wind speed U_a can be obtained from figures 2 and 4, respectively. With the values of T_o and U_a at a given location in a given month, the transfer coefficient for excess heat can be calculated by equations 10 through 13. After D, U, Z, and Q are determined, the excess temperature T_e can be computed by equation 3. The T_e thus calculated can then be used as the initial excess temperature for the next reach. Theoretically, T_e can reach zero only at infinity. In practice, a T_e value taking into account where a power plant can be built must be selected. The residual temperature ΔT at a distance X downstream from the previous power plant is the difference between T_{eo} and T_e. Once ΔT is determined, the allowable power plant capacity KW in kilowatts can be computed by equation 2 with T_{eo} replaced by ΔT, i. e.,

$$KW = 35 \, (\Delta T) \, Q \qquad (17)$$

The water discharge, flow velocity, water depth, and transfer coefficient vary from place to place along the Sangamon River. However, in equation 3, it is assumed that D, U, and Z are constants within a given reach X. It is necessary to determine the limit of X within which equation 3 can be applied without causing much error. On the basis of field experience, a 10 percent measurement error of flow velocity and water depth is tolerable. Computations are carried out according to the following procedures:

1) Determine velocity and depth at Mahomet for a given flow frequency by equations 5 and 6

2) Increase velocity and depth by 10 percent and determine their corresponding drainage area; the smaller of the two is the drainage area at the end of the first reach (reach length can be calculated by equation 14, 15, or 16)

3) Calculate the excess temperature at the end of the first reach by equation 3 with the average reach values of D, U, Z and an initial excess temperature of 5^oF

4) Use the excess temperature obtained from step 3 as the initial value for the second reach and repeat the computation until the excess temperature is reduced to a predetermined value; assign a power plant to this point; calculate its allowable capacity by equation 17; raise the excess temperature back to 5^oF and repeat steps 1 through 4 until reaching the mouth of the Sangamon River

5) At the junction of two rivers with different water temperatures, use a weighted mean temperature based on the discharges to calculate downstream temperature decay

Figure 7 shows an example of the calculated results for median flow in August.

Cost-Capacity Relationship

The steam-electric plant construction costs and annual production expenses for all major companies in the United States are published annually by the Federal Power Commission (1950-1972). Because the costs depend on the locations of power plants, only those plants in Illinois, Wisconsin, Indiana, and Iowa are included in this analysis. These costs are for land and land rights, structures and improvements, and equipment. The cost for fuel is not included because it varies widely with its source, type, and time of purchase. In order to adjust the costs of power plants built in different years to the costs in 1973, cost indexes based on 100 for 1913 were obtained from Engineering News-Record (1974). Table 3 summarizes the data used to determine the 1973 unit costs of power plants in and near Illinois. The relationship between unit cost M in dollars per kilowatt and generating capacity P in megawatts (figure 8) can be expressed by

$$M = 1621 P^{-0.31} \tag{18}$$

Figure 8 shows that the rate of decrease slows down significantly after the power plant capacity reaches 400 megawatts.

DISCUSSION

A computer program was written to calculate the transfer coefficients and amounts of excess temperature decay for different flow frequencies and residual temperatures in each month. The optimum number of power plants within each reach, their costs, and their power generating capacities could then be determined.

Table 4 shows examples of the power capacities, costs, and numbers of plants that could be built along the Sangamon River with different residual temperatures at the median flow frequency in August. The location column indicates each plant's distance in miles downstream from Mahomet (0.0). Calculated results indicate that the total allowable power generating capacity along the Sangamon River is greater when a power plant is near the junction of two rivers because there is a sudden increase of water discharge. This increase can cause a significant increase of Q and T in equation 17. The computer program was written so that

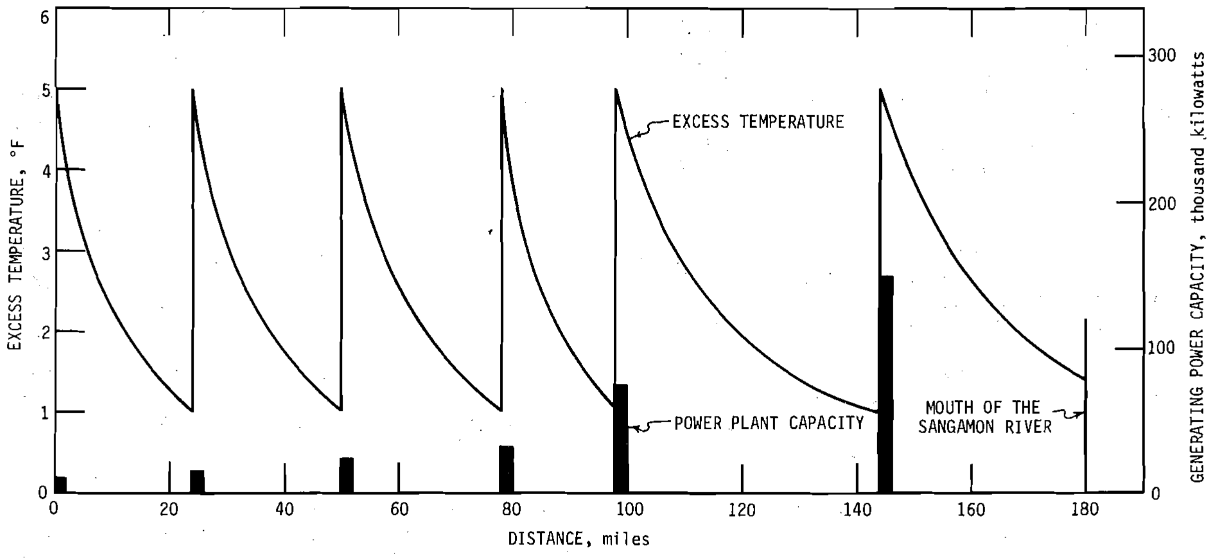

Figure 7. Calculated variation of excess temperature at power plants along the Sangamon River

Table 3. Unit Cost of Power Plants in and near Illinois

Plant name	Construction year	Capacity *(mw)*	Unit cost *($/kw)*	Cost index	1973 Cost *($/kw)*
Illinois					
Sabrooke (Rockford)	1950	20	267	375	810
Vermilion (Oakwood)	1955	60	286	469	694
E.D. Edwards (Bartonville)	1960	125	228	559	464
Marion (Marion)	1963	99	184	594	353
Coffeen (Coffeen)	1965	300	132	627	240
Kinkaid (Kinkaid)	1967	659.7	121	672	205
Wisconsin					
Menasha (Menasha)	1950	8.0	209	375	634
North Oak Creek (Oak Creek)	1954	400	110	446	281
Rock River (Beloit)	1954	75	165	446	421
Stoneman (Cassville)	1954	51.8	144	446	367
Weston (Rothchild)	1955	60	172	469	417
Nelson Dewey (Cassville)	1960	100	167	559	340
South Oak Creek (Oak Creek)	1961	550	126	568	252
New Genoa (Genoa)	1969	345.6	136	790	196
Indiana					
Tanners Creek (Lawrenceburg)	1951	125	168	401	477
Whitwater Valley (Richmond)	1955	30	204	469	495
F.B. Culley (Yankeetown)	1955	40	209	469	704
Dean Mitchell (Gary)	1957	138.1	165	509	369
Gallagher (New Albany)	1959	300	150	548	311
Breed (Sullivan)	1960	450	162	559	330
Bailly (Dune Acres)	1963	194	178	594	341
Warrick (Newburgh)	1966	432	133	650	233
Petersburg (Petersburg)	1967	261.7	124	672	210
Iowa					
Bridgeport (Eddyville)	1953	40.0	239	431	631
Council Bluff (Council Bluff)	1954	44.0	278	446	709
Sutherland (Marshalltown)	1955	60.	199	469	483
Wisdom (Spencer)	1960	37.5	203	559	413
Montpelier (Montpelier)	1960	69.1	162	559	330
Neal (Salix)	1964	147.1	137	612	255

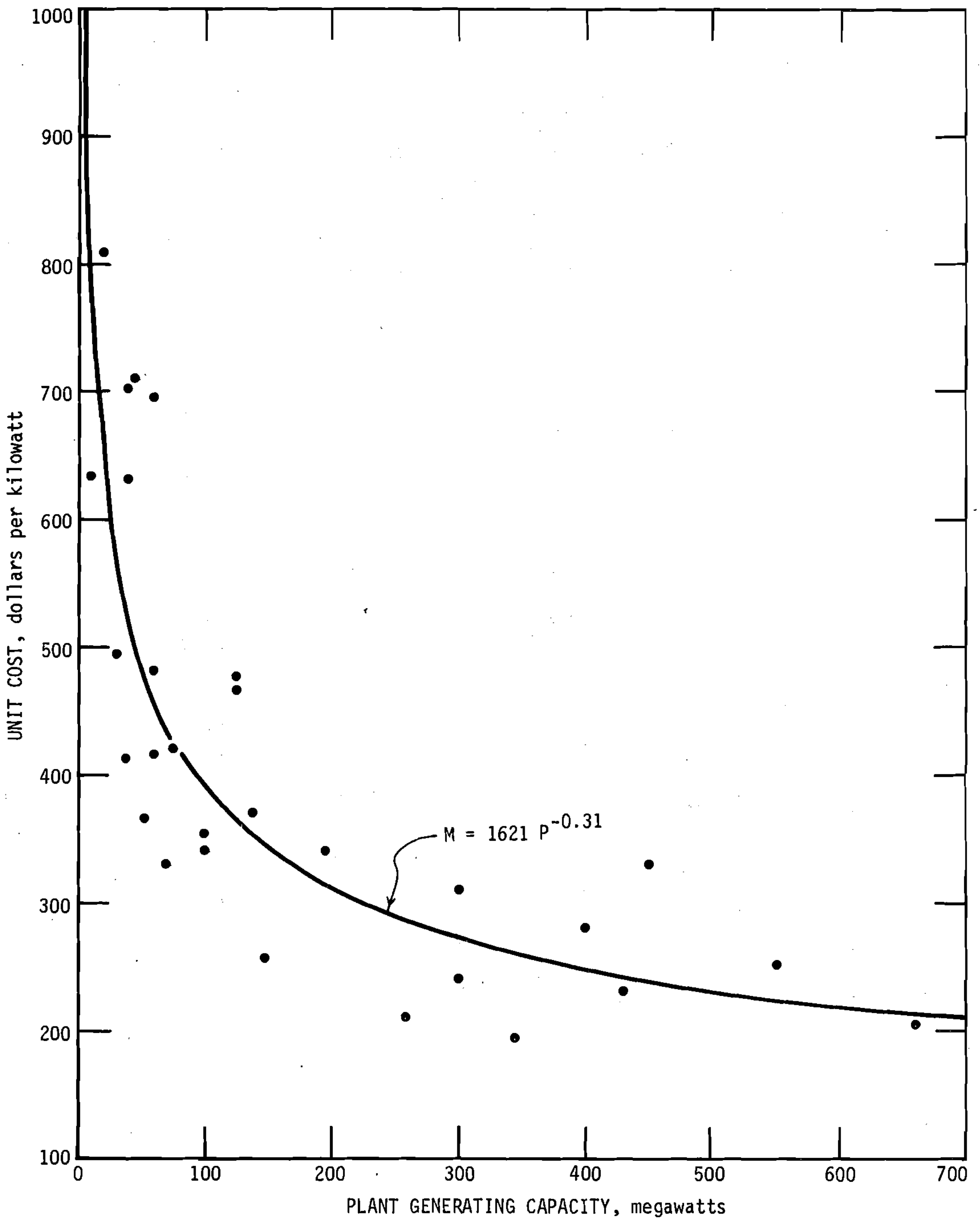

Figure 8. Relationship between unit cost and power plant capacity

Table 4. Optimum Number of Power Plants, Their Costs and Their Capacities

Residual Temperature *(°C)*	Location Distance *(mi)*	Power capacity *(mw)*	Total capacity *(mw)*	Cost (10^6 *dollars*)	Total cost (10^6 *dollars*)	Total number of plants
3.0	0.0	10.2		8.1		
	13.2	8.8		7.3		
	28.2	12.1		9.0		
	43.3	15.7		10.8		
	59.2	19.5		12.6		
	76.7	23.5		14.3		
	94.7*	53.8		25.3		
	119.4	62.6		28.1		
	143.5**	113.3	319.3	42.4	157.9	9
3.5	0.0	10.2		8.1		
	17.7	11.4		8.7		
	36.8	16.5		11.2		
	57.6	22.3		13.8		
	79.0	28.3		16.3		
	94.7	62.8		28.2		
	143.5**	132.2	283.6	47.1	133.4	7
4.0	0.0	10.2		8.1		
	24.0	15.0		10.5		
	50.1	23.1		14.1		
	77.6	31.7		17.6		
	97.9	74.0		31.6		
	143.5**	151.0	305.0	51.7	133.5	6
4.5	0.0	10.2		8.1		
	35.1	20.6		13.1		
	75.0	34.9		18.8		
	112.6	91.1	156.9	36.5	76.4	4

note: * junction of the main stem and the South Fork
** junction of the main stem and the Salt Creek

when the second power plant is located within 5 percent of the distance between the first power plant and a river junction, it is assumed that the second power plant will be built immediately below the junction. Because the tributaries of the Sangamon River are small, no power plant will be built along them.

Figure 9 shows an example of the relationship between total power generating capacity and residual temperature for different flow frequencies in August. At high flow ($F = 0.1$), the total power generating capacity is highly variable. Because of the high velocity at high flow, a small difference in residual temperature can cause significant differences in power plant locations and number of power plants. The physical makeup of the Sangamon River stream system accounts for the irregular shape of the $F = 0.1$ curve in figure 9. At low flows ($F = 0.5$ or 0.9) total generating capacity is less, and decreases slightly with increasing T values. In this case it is more economic to build fewer power plants with larger individual capacities along the Sangamon River.

The relationship between total power plant cost and residual temperature for different flow frequencies in August is shown in figure 10. With the exception of high flows, total power plant cost decreases with increasing residual temperature.

Figure 11 shows the variation of total power generating capacity at median flow in different months. It indicates that the total power generating capacity in summer is higher than that in winter. This is the opposite of what one would expect but, according to equation 12, the transfer coefficient has a higher value in summer. Thus, the water cools faster and this reduces the required distance between power plants so that more can be built along the Sangamon River. A study of the complete computer results for different combinations of flows frequencies, months, and residual temperatures indicates that a maximum power generating capacity can be obtained for the Sangamon River when the residual temperature is within the range of $2^{o}F$ to $3.5^{o}F$. Because the transfer coefficient for excess heat has a lower value, and because water discharge is also low in winter, winter is the critical time for allowable generating capacity of a power plant.

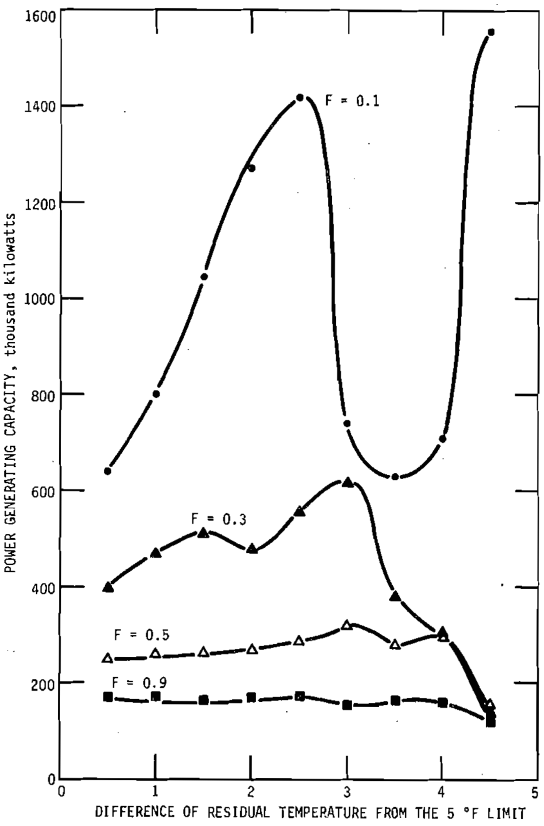

Figure 9. Relationship between total power generating capacity and residual temperature

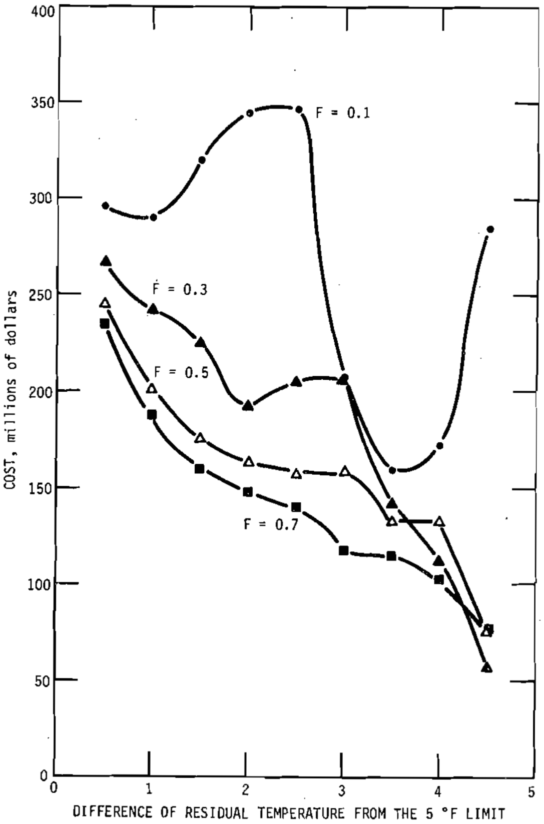

Figure 10. Relationship between total cost and residual temperature

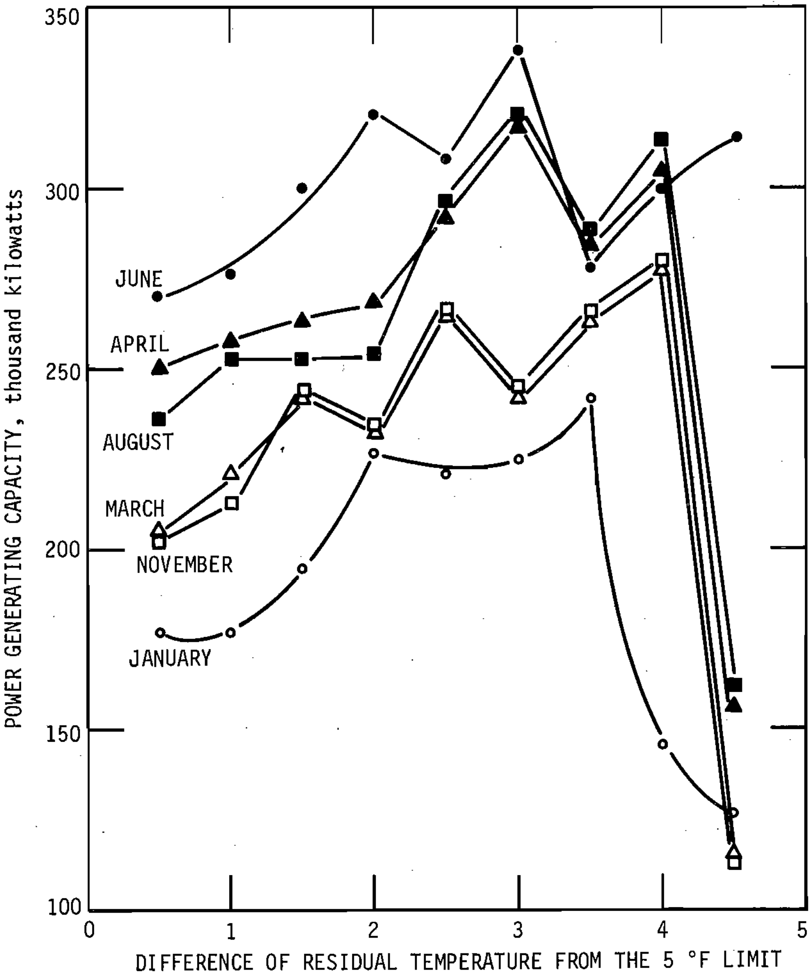

Figure 11. Relationship between total power generating capacity and residual temperature

CONCLUSIONS

Hydrologic and climatic data measured in and near the Sangamon River Basin were analyzed to determine the heat assimilative capacity of the Sangamon River. The restrictions were that water temperature cannot exceed 90°F and the maximum allowable excess temperature is 5°F. The following conclusions have been reached.

1) The surface transfer coefficient for excess heat depends mainly on wind speed and natural water temperature. This coefficient can be approximated by four equations for different ranges of wind speed.

2) The surface transfer coefficient for excess heat has a higher value in summer than in winter. For a given flow frequency and allowable residual temperature, the heat assimilative capacity of a river is higher in summer than in winter. Winter is thus the critical time in the determination of allowable power generating capacity.

3) The allowable generating capacity of a power plant can be highly sensitive to its location along a river. Within reasonable distance, a power plant should be located immediately downstream of the junction of a tributary to increase its allowable capacity.

4) The unit cost per kilowatt of electric power output decreases with increasing power plant capacity. The rate of decrease slows down significantly after the power plant capacity reaches 400 megawatts.

5) The total allowable power generating capacity along a river depends on the residual temperature. At low flows, the total allowable power generating capacity decreases with increasing residual temperature.

6) Optimization techniques should be used to select a residual temperature such that total power generating capacity along a river can be maximized and the total cost can be kept at a reasonably low value.

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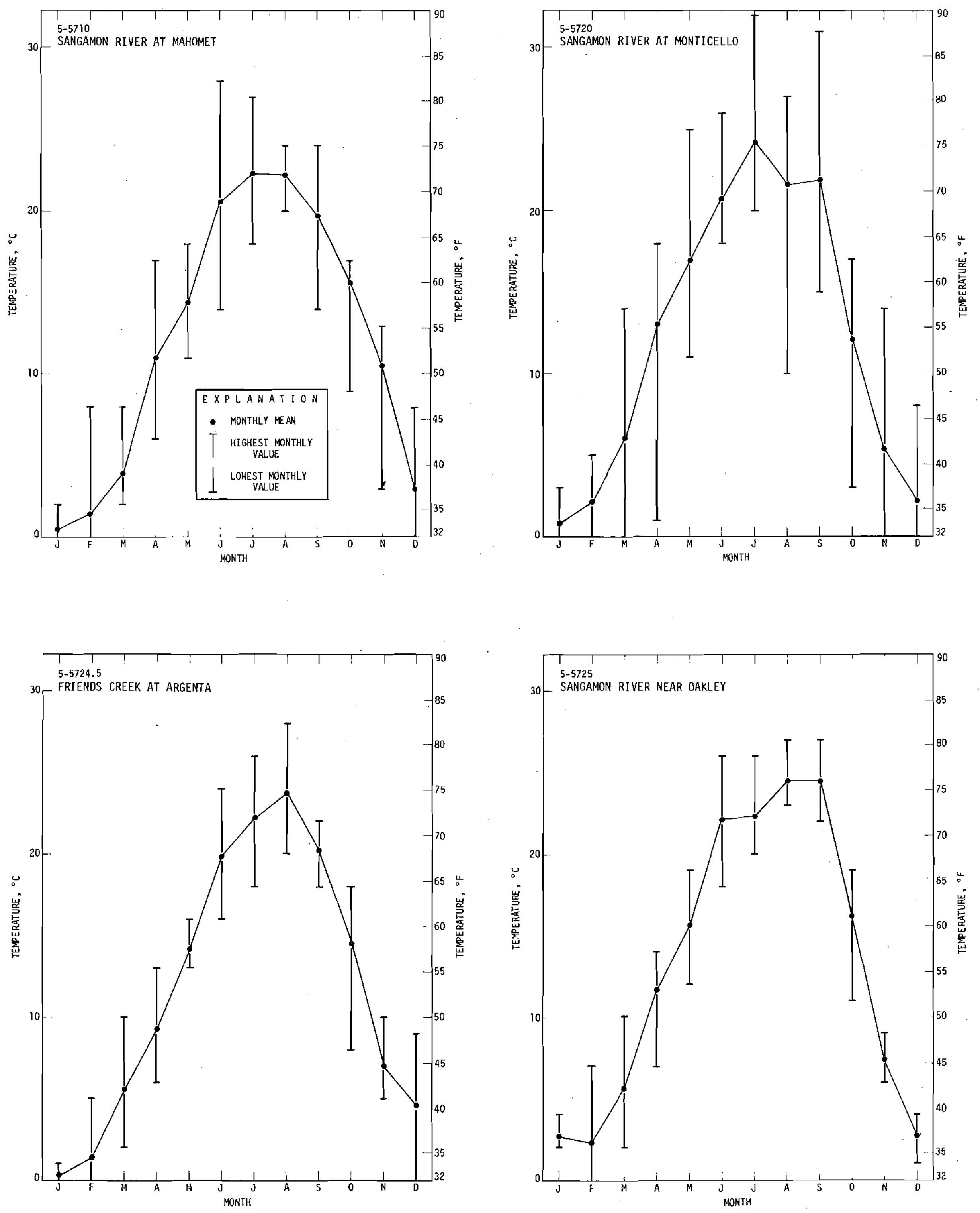
APPENDIX

Variation of Monthly Water Temperature, Sangamon River Basin



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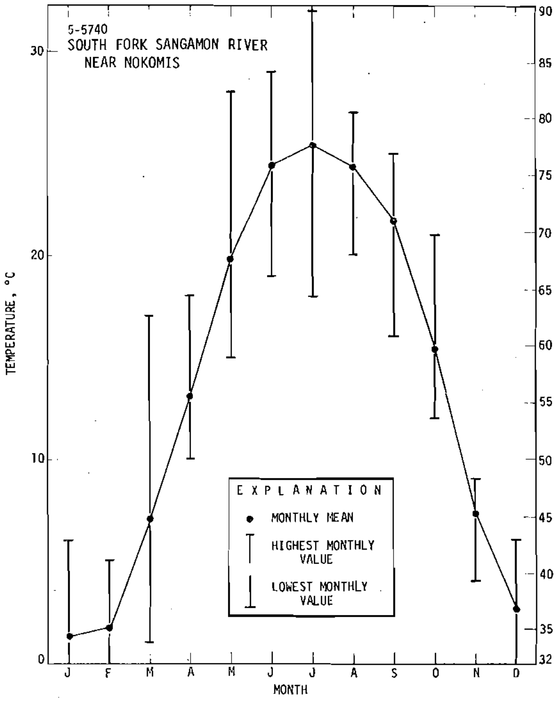

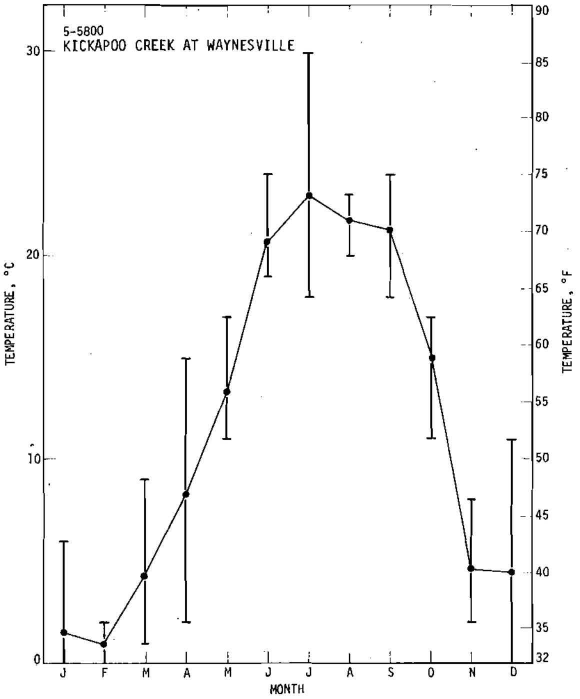

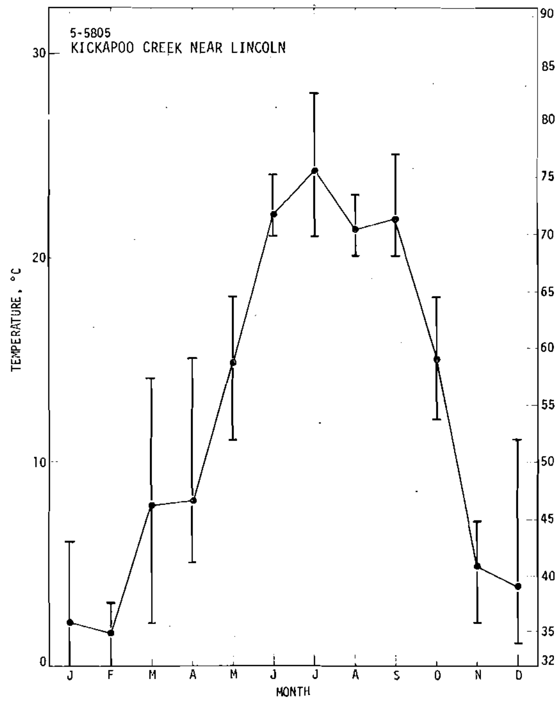

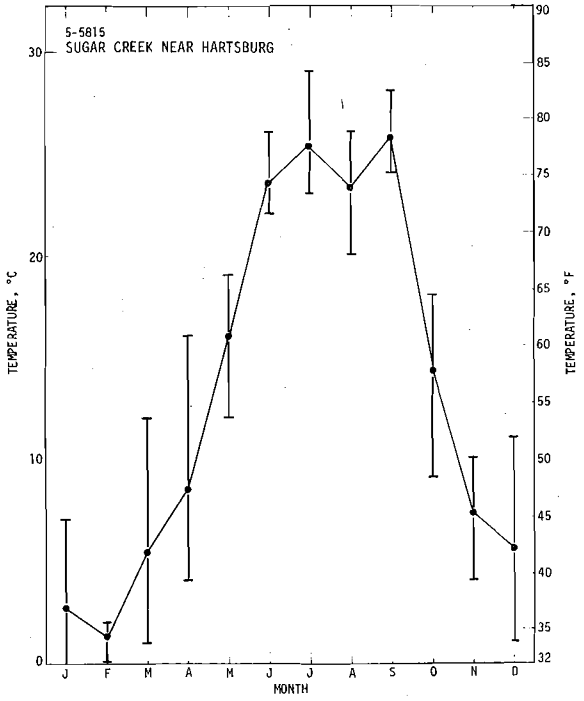

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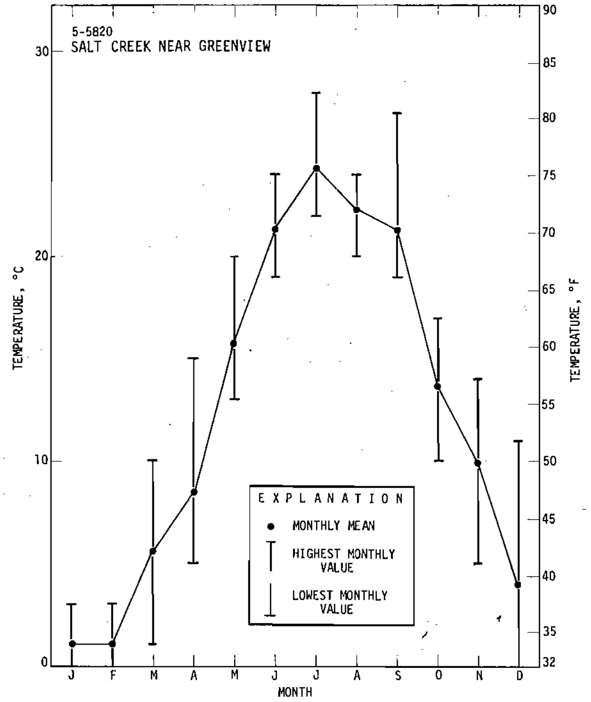

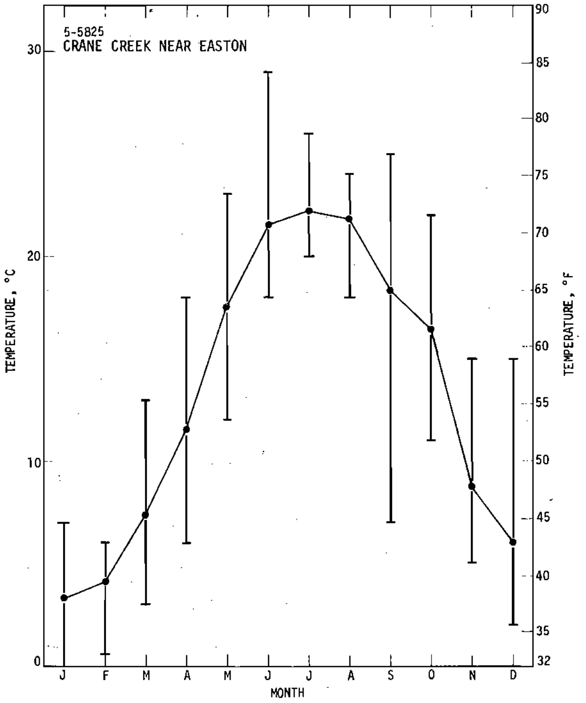

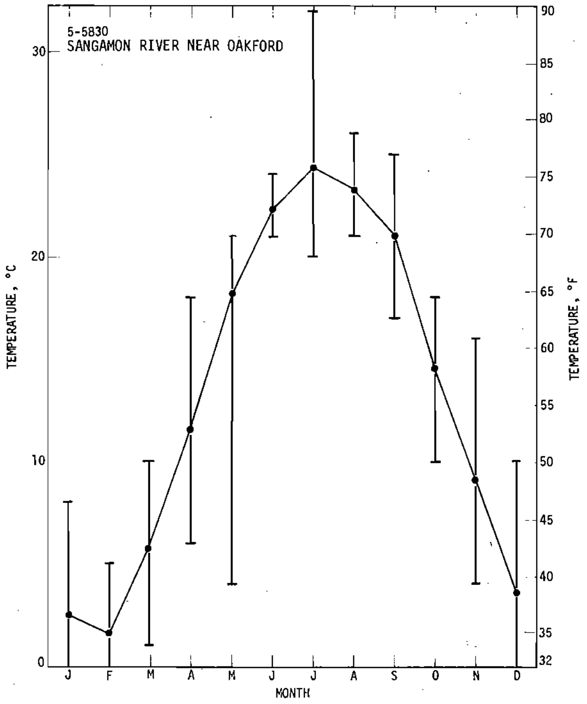

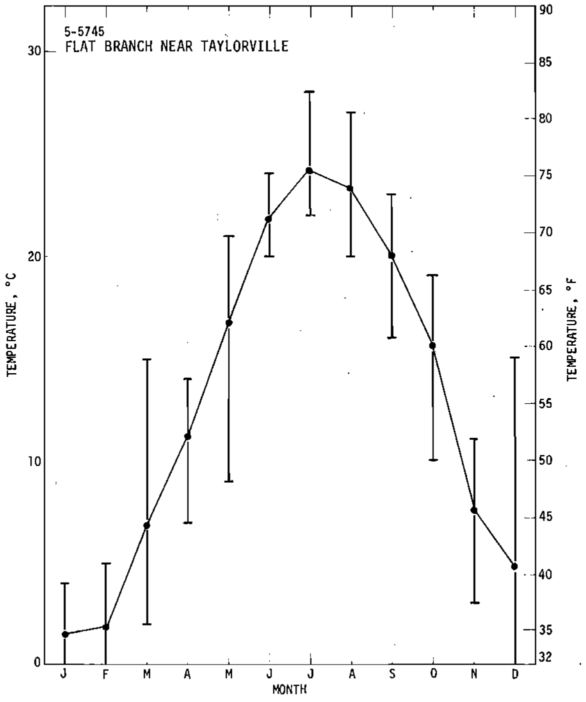

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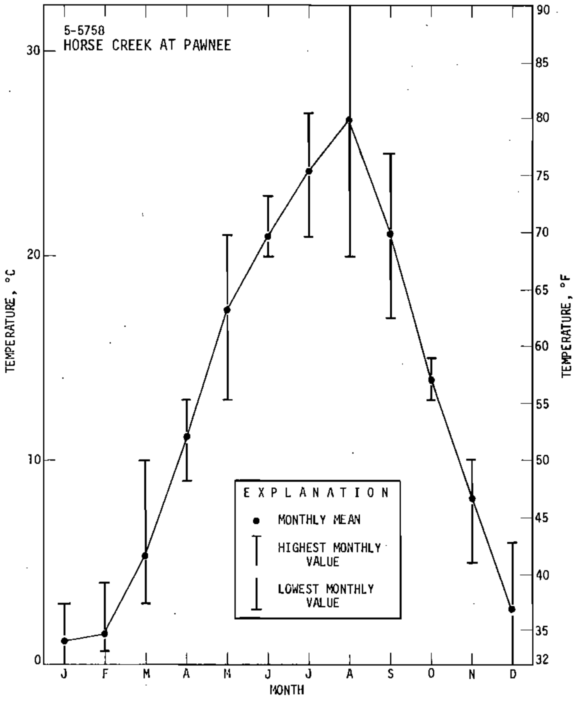

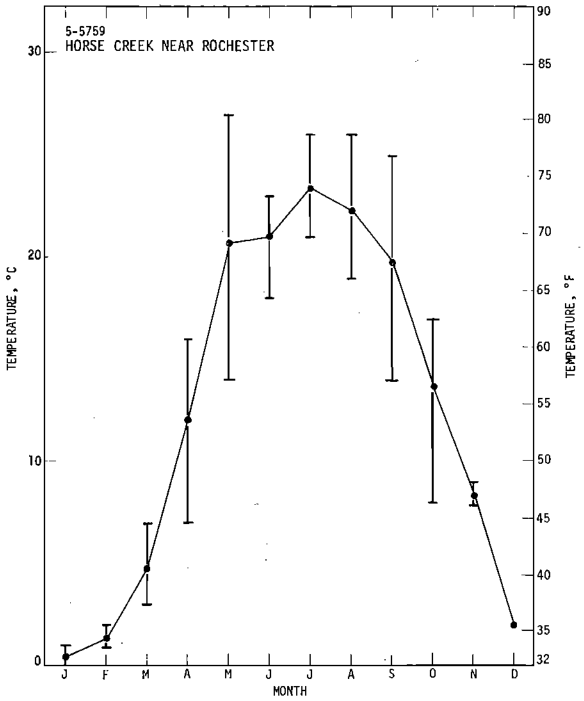

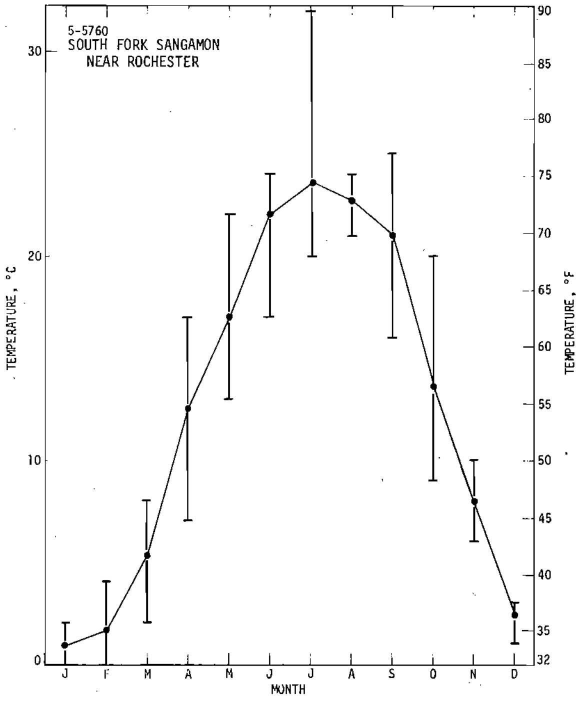

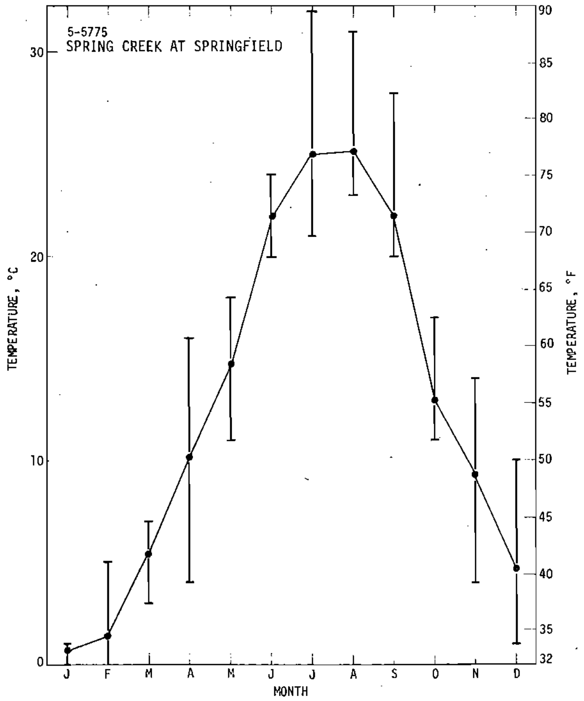

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