Thermal Load Allocations for Power Plants in the Lower Wabash River

A. Hossain and B. Jacobs
Water Pollution Control Division
Indiana State Board of Health, Indianapolis, Indiana 46206

Abstract

This study reports the strategies of thermal load allocations for the five power plants in the lower Wabash River. A one dimensional river temperature prediction model was used to allocate thermal loads. Results indicate that for summer seven-day 1-in-10-year low flow, and also for seven-day 1-in-10-year low flow, the limiting condition was not the maximum monthly limiting temperature of the river, but the maximum temperature rise above ambient temperature. This is five degrees Fahrenheit (2.7°C) for the Wabash River as per Indiana Stream Pollution Control Board's SPC 1R-3. For the first power plant, the limiting condition was the upstream river water temperature.

Introduction

The electric power industry requires cooling water in order to efficiently generate electricity. The water withdrawn by a power plant for once-through cooling systems circulates through the power plant condensers and absorbs most of the heat retained by the steam after it leaves the turbine and before the condensate is returned to the feedwater heaters and boilers. The quantity of water required for this purpose varies depending upon plant size, plant heat rate, and the acceptable temperature rise of the cooling water. Returning the now-heated water directly to the stream from which it was withdrawn may contribute to stream pollution.

The segment of the Wabash River considered for this study includes about 84 miles from Cayuga, Indiana, to near Hutsonville, Illinois (Figure 1). The purpose of this study is to estimate the allowable heat discharge for the following power plants located in this reach of the Wabash River: Cayuga Power Generating Station, Wabash Power Generating Station, Dresser Power Generating Station, Breed Power Generating Station, and Hutsonville Power Generating Station (Figure 1). After this study service from Dresser Power Generating Station was discontinued.

Biological Considerations

A reach of the Wabash River adjacent to the Wabash Generating Station was taken as the study area for the analysis of biological effects of the thermal discharge for said plant (3). A segment of the river approximately 3.5 km long, 122 m wide, and averaging less than 3 m deep (during summer low flows) was divided into ten subareas. Save for a shallow riffle area, the subareas were fairly homogeneous in depth, woody cover and bottom substrate. Although ten subareas were defined, they were combined into three thermal zones: Zone 1, a cool upstream section; Zone 2, a short, hot section near the power plant effluent which averaged 7-9°C (13-16°F) above ambient; and Zone 3, a long, varied (both temporally and spatially) thermal area

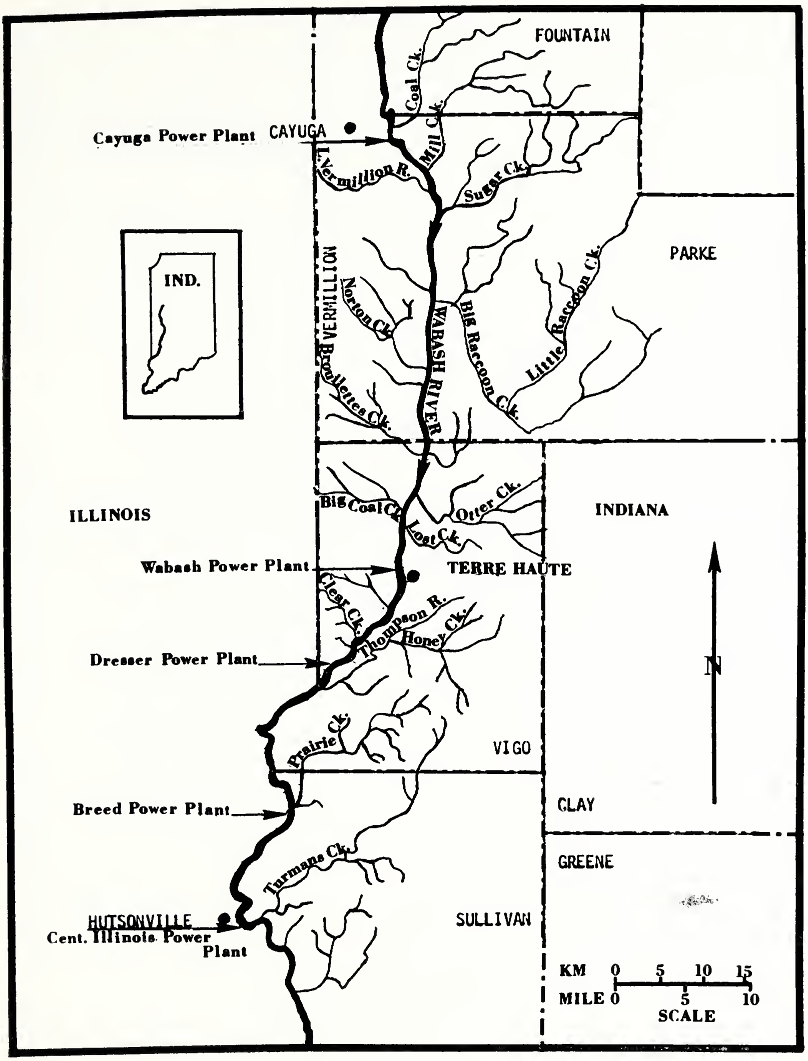

FIGURE 1. *Location Map*

downstream of the mixing zone which averaged 1-3°C (2-5°F) above ambient.

The study area for the Cayuga Generating Station was unique in the respect that it contained all of the various habitats (except backwater areas) found in the Wabash River. Ultimately, a 5.2 km segment was divided into eight subareas. Each subarea was nearly homogeneous concerning habitat type. The various habitats ranged from shallow, sandy bottoms with sluggish flows, through strongly flowing water with mud banks and little cover, to gently flowing gravel-bottomed beds with woody bank cover.

A variety of capturing methods were used for fish, but it was found that electrofishing with pulsating D.C. current produced better results than hoop or ridged "D" nets. Providing an artificial substrate proved to be the most effective means for sampling macroinvertebrates.

The regularity of the behavioral responses was sufficient enough to justify the use of catch data for the Wabash Generating Station area to validate the establishment of optimum temperature ranges for species in the Cayuga area. As predicted, species that were expected to avoid the heated areas (including goldeye, redhorse, sauger, skipjack herring and various centrarchids) did, while those that were expected to be attracted to the warmer segments (gar, carp, flathead catfish, and carpsuckers) were.

Strategies for Thermal Load Allocations

The strategy used in this report for allocating thermal loads for the five power plants in this reach of the Wabash River was based on meeting the water quality standard specified in the Indiana Stream Pollution Control Board's Regulation SPC 1R-3 (4). The SPC 1R-3 has three general types of water temperature criteria that must be met. These are: a) monthly maximum allowable temperatures which are 90°F in June through September; b) a maximum allowable temperature increase which is 5°F above a defined base temperature; and c) an allowable mixing zone at the edge of which, temperature criteria must be met.

Moreover, the thermal effluent limitations guidelines set forth as mandated by Public Law 92-500 dictates that all existing power plants must use "Best Practicable Control Technology currently Available" (BPT) to reduce thermal loads by no later than July 1, 1977. Also the existing power plants must use "Best Available Technology Economically Achievable" (BAT) to reduce thermal load by no later than July 1, 1983 (7). The above reference also gives the criteria for exemption to the thermal limits required by the best practicable control technology currently available or the best available technology economically achievable.

Alternative strategies to allocate thermal load for the power plants which will not violate SPC 1R-3 are given in appendix I.

Model Used

There are two fundamental approaches to the study for predicting heat loss in a flowing stream. One formulation of the heat dissipation is based on energy budget relationships and the other is the empirical approximation.

Ohio River Valley Water Sanitation Commission (ORSANCO) used their model STREAM (5) solely for Ohio River temperature prediction. In this model the temperature change is estimated based on the exponential die-away of the difference between the river temperature and the estimated normal temperature of the river.

Edinger-Geyer's(2) one dimensional model was used to predict temperatures along a river. The model basis is a heat budget which is used to determine an equilibrium temperature and a heat exchange coefficient. The model COLHEAT developed by Raphael (6) employs a heat budget to simulate the effect of the local environment on the rate of heat exchanged between the water body and the atmosphere. The analytical models of thermal discharges available for flowing streams may also be classified by regions affected by heated dischargers such as near field, far field, and broad thermal trends. This may also be classified based on type of discharge such as submerged discharges, surface discharges, etc. A review of the analytical modeling of thermal discharges is given by Benedict et. al (1).

The amount of data necessary to use any elaborate model for predicting river water temperature was not available for the present study, so a simple empirical model developed by LeBosquet (8) was used. This method of predicting heat loss in a flowing stream is based on the assumption that the rate of decrease of temperature differential between air and water, when the temperature of the air remains constant, is a constant proportion of the remaining temperature differential. This is expressed in mathematical form as follows:

$$-\frac{dT}{dt} = KT \qquad (1)$$

Where
T = Temperature differential between air and water
K = Constant
t = Time

By integrating equation (1), expressing it in common logarithmic form and substituting $K = \frac{UA}{G}$ equation (2) is obtained

$$\log \frac{T_1}{To} = \frac{-(U \times 0.0102 \times W \times D)}{Q} \qquad (2)$$

Where
T_1 = Temperature differential between water and air at any time t.
To = Initial temperature differential.
A = Surface area of stream, sft (Cm/929)
D = Distance along the river course, miles (Km/1.609)
W = Mean width of stream channel, ft (Cm/30.48)
G = Weight of water between two locations, lb (Kg/2.2)
Q = Runoff of the stream, cfs (m^3/sec/0.0283)
U = Coefficient of heat transfer, BTU/Hr. (erg/sec/2.93×10^6)

If river water temperatures are observed at two locations D0 and D1, equation (2) may be written as equation (3)

$$U = \frac{}{0.0102 \times W \times D} \cdot (\log T_{D0} - \log T_{D1}) \qquad (3)$$

Where

T_{D0}, T_{D1} = Temperature differential between water and air at locations D0 and D1, respectively, degrees Fahrenheit (Celsius/0.55)

The following data are required for the model to calculate the river water temperature downstream of a thermal effluent discharger and the upstream river water temperature of the next discharger in a stream system: number of reaches the stream system is divided into, average air temperature, mean width of stream channel for each reach, length of each reach, discharge of the stream in each reach, coefficient of heat transfer, total heat load of each thermal effluent discharger.

The data used for the determination of coefficient of heat transfer, U, were obtained by U.S. Environmental Protection Agency's Evansville office for a reach of 6.5 miles (10.46 km) below Cayuga Power Plant. The U value was estimated as 23.8 BTU/HR - sq. ft - ^{0}F (136.3 Joules/sec-m$_2$-^{0}C). Figure 2 shows the plot of computed river water temperature and measured average river water temperature with distance on October 10, 1974. The data used are given in Table 1.

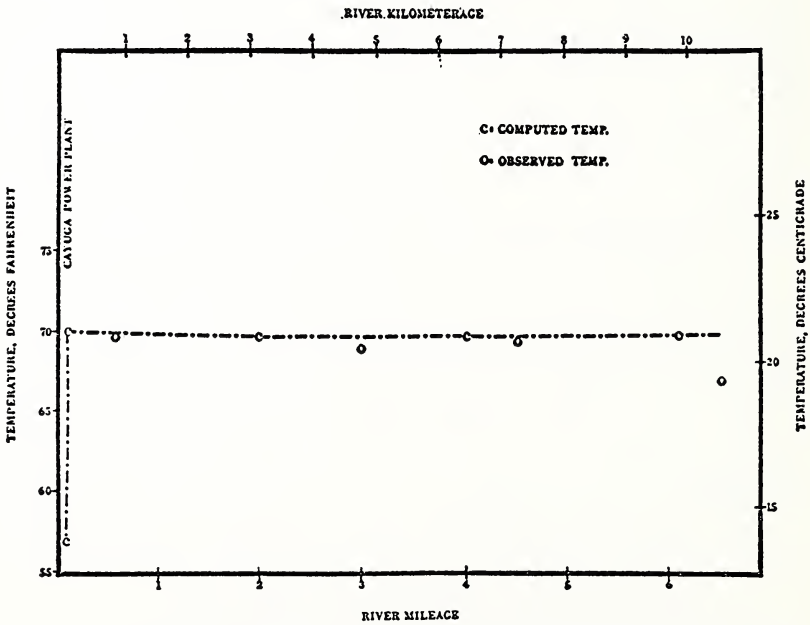

FIGURE 2. *Computed and measured river water temperature downstream of Cayuga Power Plant*

Results

The purpose of the model is to determine the allowable thermal loads which would not violate the SPC 1R-3 for summer seven-day 1-in-10-year low flow and seven-day 1-in-10-year low flow.

The data used for the low flow characteristics (seven-day 1-in-10-year and summer seven-day 1-in-10 year) of the Wabash River at the location of power plants were estimated by interpolating the low flow data at the USGS gauging stations at Covington, at Montezuma, at

Terre Haute, and at Riverton (Table 2). The river water temperature at Lafayette was used for estimating the intake water temperature of Cayuga Power Plant. The data used are shown in Table 3.

The estimated maximum heat load of the plants used for this study is shown in Table 4. For the present study, air temperature over the reach of the Wabash River considered was taken equal to the air temperature of Terre Haute. The data used is shown in Table 3.

TABLE 1. *Data used for verification of the model*

Tran.	Location	River Width ft(m)	Avg. Water temp. °F(°C)	Air temp., °F(°C)	River Flow, cfs(m^3/sec)
1	300 ft(91m) upstream of Cayuga Power Plant intake	352 (107)	57.2 (14.0)	62 (16.7)	1921 (54.4)
2	50 ft(15m) downstream of heated water discharge	272 (83)	64.7 (18.2)	68 (20.0)	1921 (54.4)
3	2500 ft(16m) downstream of heated water discharge	389 (118)	69.6 (20.9)	68 (20.0)	1921 (54.4)
4	3 miles (4.8km) downstream of heated water discharge	469 (143)	69.4 (20.8)	70 (21.1)	1921 (54.4)
5	4.5 miles (7.2km) downstream of heated water discharge	308 (94)	69.6 (20.9)	70 (21.1)	1921 (54.4)
6	6.5 miles (10.5km) downstream of heated water discharge	434 (132)	66.8 (19.3)	62 (16.7)	1921 (54.4)

Thermal effluent discharge of the Power plant = 1248 cfs ($35.3 m^3$/sec)
U value used = 23.8 Btu/Hr-ft^2°F (1.36×10^9 erg/sec-m^2-°C)
Average air temperature = 66.7°F (19.3°C)

TABLE 2. *Low Flow of Wabash River*

Location	Drainage Area, Sq. Mile (sq. km)	Summer Seven Day 1 in 10 Yr. cfs (m^3/sec)	Seven Day 1 in 10 Yr. cfs (m^3/sec)
Wabash River at Covington	8,208 (21,258)	820 (23.2)	660 (18.7)
Wabash River at Cayuga Plant	10,006 (25,915)	920 (26.0)	753 (21.3)
Wabash River at Montezuma	11,100 (28,749)	980 (27.7)	810 (22.9)
Wabash River at Wabash River Power Plant	12,162 (31,499)	1,154 (32.6)	926 (26.2)
Wabash River at Terre Haute	12,200 (31,598)	1,160 (32.8)	930 (26.3)
Wabash River at Dresser Power Plant	12,423 (32,175)	1,249 (35.3)	972 (27.5)
Wabash River at Breed Power Plant	12,796 (33,141)	1,398 (39.6)	1,043 (29.5)
Wabash River at Hutsonville Power Plant	13,048 (33,794)	1,499 (42.4)	1,090 (30.8)
Wabash River at Riverton	13,100 (33,929)	1,520 (43.0)	1,100 (31.1)

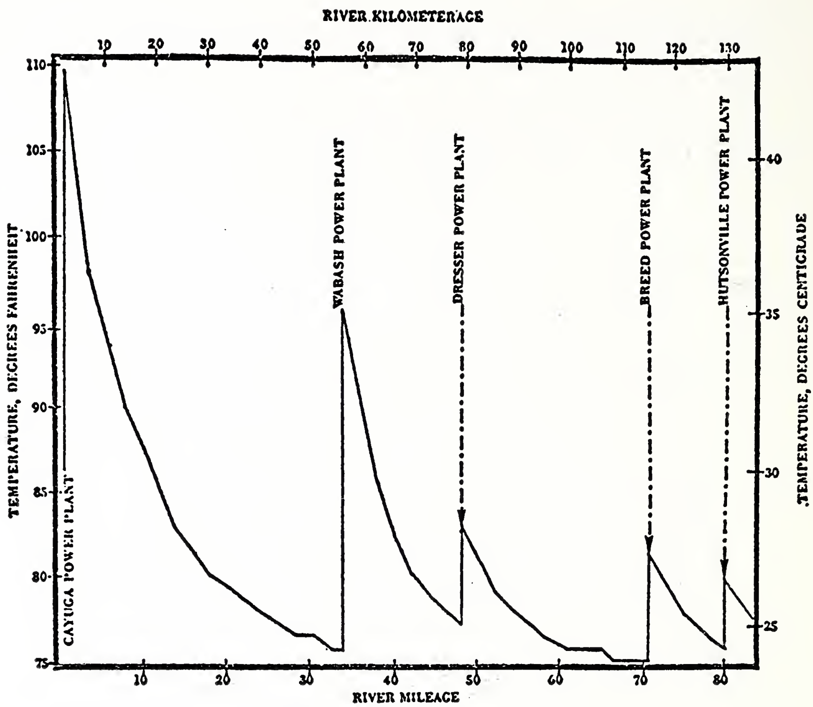

FIGURE 3. *River water temperature with distance for summer seven day one in ten year low flow*

The model was simulated for the seven-day, 1-in-10-year low flow and for the summer seven-day 1-in-10-year low flow. Figures 3 and 4 show the plot of river water temperature with distance for seven-day, 1-in-10 year low flow and for the summer seven-day, 1-in-10 year low flow respectively. The heat load used from the power plant is shown in Table 4.

Discussions and Conclusions

The computed river water temperature compares fairly well with the measured river water temperature (October 10, 1974), after mixing, except for the last transect as shown in Figure 2. This may be explained by the fact that for the model an average air temperature was used, whereas, in actual condition, there was a rapid drop of air temperature from 70°F (21.1°C) to 62°F (16.6°C) between transect 5 and transect 6.

It is obvious from Figure 3 that with summer seven-day, 1-in-10 year low flow and with maximum thermal loads for the power plants there would be violations of SPC 1R-3 below the first four power plants. It was found that if the heat loads for the first four power plants were reduced to meet the SPC 1R-3, the Indiana Stream Regulation would not be violated below Hutsonville Power Plant for the maximum

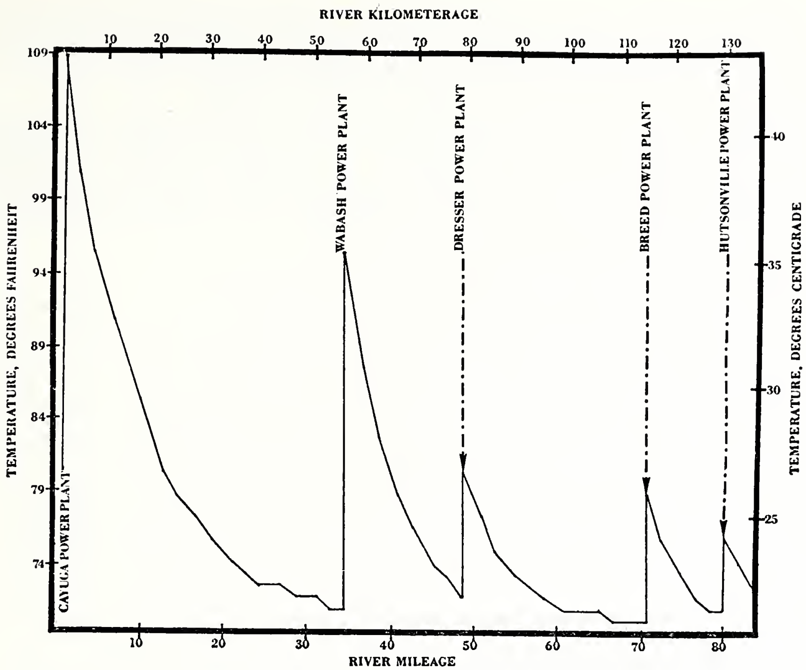

FIGURE 4. *River water temperature with distance for seven day one in ten year low flow*

heat load of that power plant. This is also true for seven-day 1-in-10-year low flow.

It was found that with the variation of coefficient of heat transfer, U, the amount of heat that the first four power plants would have to reduce did not vary. This is due to the fact that during summer seven-day, 1-in-10-year low flow the limiting condition is not the maximum monthly limiting temperature of the river, but the maximum temperature rise above ambient temperature which is 5°F (2.8°C) for the Wabash River. For the Cayuga Power Plant, the limiting condition is the upstream river water temperature. The maximum rise of river water temperature allowable for summer months is 90°F (32.2°C). Therefore, the amount of heat that could be discharged by the Cayuga Power Plant when the upstream river water is 86.9°F (30.5°C) should not increase the temperature downstream after mixing more than 3.1°F (1.7°C).

For the present study, the allowable heat loads that the five power plants could put into the Wabash River were based on seven-day 1-in-10-year low flow and summer seven-day 1-in-10-year low flow. There are a few questions that could be asked about the values used in the model for the thermal load allocations:

What river water temperature upstream of Cayuga Power Plant should be used: it may be average monthly water temperature for summer months, summer seven-day 1-in-ten-year daily mean temperature or maximum daily mean temperature, or some other temperature? For this study no correction factor was applied for the change of river water temperature between Lafayette and Cayuga.

What air temperature over the river reaches should be used: it may be the maximum monthly temperature for summer months, the daily maximum air temperature for summer months, summer seven-day 1-in-10-year maximum daily mean temperature or any other air temperature?

TABLE 3. *Data used for thermal load allocations*

Summer 7 day in 10 year low flow:

	Cayuga Power Plant	Wabash River Power Plant	Dresser Power Plant	Breed Power Plant	Hutsonville Power Plant
Flow, cfs (m^3/sec)	920 (26.0)	1154 (32.6)	1249 (35.3)	1398 (39.6)	1499 (42.4)
Thermal load from Power Plants, Btu/Hr (Joules/sec)	47.99×10^8 (1.41×10^9)	49.88×10^8 (1.46×10^9)	17.38×10^8 (5.09×10^8)	20.05×10^8 (5.87×10^8)	12.35×10^8 (3.61×10^8)
River water temperature above Cayuga Power Plant, °F (°C)	86.9 (30.5)				
Air temperature over the reaches, cf (°C)	75.6 (24.2)	75.6 (24.2)	75.6 (24.2)	75.6 (24.2)	75.6 (24.2)
Width of river, ft (m)	173 (52.7)	340 (103.6)	360 (109.7)	458 (139.6)	460 (140.2)
Coefficient of heat transfer, Btu/Hr-ft^2°F (erg/sec-m^2°C)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)

7 day 1 in 10 year low flow:

	Cayuga Power Plant	Wabash River Power Plant	Dresser Power Plant	Breed Power Plant	Hutsonville Power Plant
Flow, cfs (m^3/sec)	753 (21.3)	926 (26.2)	972 (27.5)	1043 (29.5)	1090 (30.8)
Thermal load from Power Plants, Btu/Hr (Joules/sec)	47.99×10^8 (1.41×10^9)	19.88×10^8 (1.46×10^9)	17.38×10^8 (5.07×10^8)	20.05×10^8 (5.87×10^8)	12.35×10^8 (3.61×10^8)
River water temperature above Cayuga Plant, °F (°C)	80.6 (27)				
Air temperature over the reaches, °F (°C)	70.5 (21.4)	70.5 (21.4)	70.5 (21.4)	70.5 (21.4)	70.5 (21.4)
Width of river, ft (m)	145 (44.2)	290 (88.4)	300 (91.4)	445 (135.6)	450 (137.2)
Coefficient of heat transfer, Btu/Hr-ft^2°F (erg/sec-m^2-°C)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)	23.8 (1.36×10^9)

TABLE 4. *Maximum heat load of the power plants*

Plant Name	Name Plate Capacity MW	Total Heat to cooling, Btu/Hr (Joules/sec)
Cayuga Power Plant	1011	$47.99x10^8(1.41x10^9)$
Wabash River Power Plant	970.25	$49.88x10^8(1.46x10^9)$
Dresser Power Plant	221	$17.38x10^8(5.09x10^8)$
Breed Power Plant	450	$20.05x10^8(5.87x10^8)$
Hutsonville Power Plant	215	$12.35x10^8(3.61x10^8)$

What thermal loads should be used for the power plants: all power plants may discharge maximum thermal loads, or one plant is at maximum and the rest of the plants may discharge average thermal loads?

At present, there is no guideline available for the above variables. The following conclusions may be drawn from this study:

1) For summer seven-day 1-in-10-year low flow and also for seven-day 1-in-10-year low flow with maximum thermal loads for the power plants there would be violations of SPC 1R-3 below the first four power plants.
2) For the above low flow conditions, the limiting condition is not the maximum monthly limiting temperature of the river, but the maximum temperature rise above ambient temperature which is 5°F (2.7°C) for the Wabash River.

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Appendix I

In order to take advantage of seasonal changes in river flow and water temperature so that during periods of high flow and low water temperature additional amounts of thermal load could be discharged, the following scheme may be adopted to satisfy the SPC 1R-3:

$$\frac{Q_{UP} \cdot T_{UP} + Q_{EF} \cdot T_{EF}}{Q_{UP} + Q_{EF}} = T_{ALL} \leqslant \text{Monthly maximum river water temperature allowed under SPC 1R-3} \quad \text{(A1)}$$

$$T_{ALL} - T_{UP} = 5°F \quad (2.78°C) \quad \text{(A2)}$$

Where

Q_{UP} = Upstream river discharge.

T_{UP} = Upstream river water temperature.

Q_{EF} = Effluent flow from the power plant.

T_{EF} = Effluent temperature.

By knowing the upstream river discharge and temperature, the effluent flow and temperature of the plant may be regulated so that downstream temperature, T_{ALL}, after mixing satisfies equations A1 and A2. Another alternative would be to monitor upstream and downstream river water temperatures, T_{UP} and T_{ALL} respectively. The effluent flow and temperature may be adjusted so that T_{ALL} and T_{ALL} - T_{UP} meet the SPC 1R-3.