EVALUATION OF THE IMPACT OF PHOSPHORUS REMOVAL AT THE DANBURY, CONNECTICUT SEWAGE TREATMENT PLANT ON WATER QUALITY IN LAKE LILLINONAH

by

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INTRODUCTION

In the summer of 1977, phosphorus removal by iron precipitation was initiated at the Danbury, Connecticut wastewater treatment plant (STP), a trickling filter plant serving about 35,000 people (Cervera, 1977). The primary purpose of this activity was to demonstrate the technical and economic feasibility of this approach in Connecticut.

The wastewaters from the Danbury sewage treatment plant are discharged into a brook which enters the Still River. Within a few kilometers, the Still joins the Housatonic River about 0.2 km above Lake Lillinonah (See Figure 1). Lake Lillinonah is a long, narrow (16 x 0.5-1 km) impoundment, created for electric power generation on the Housatonic River in western Connecticut. Some of its general physical

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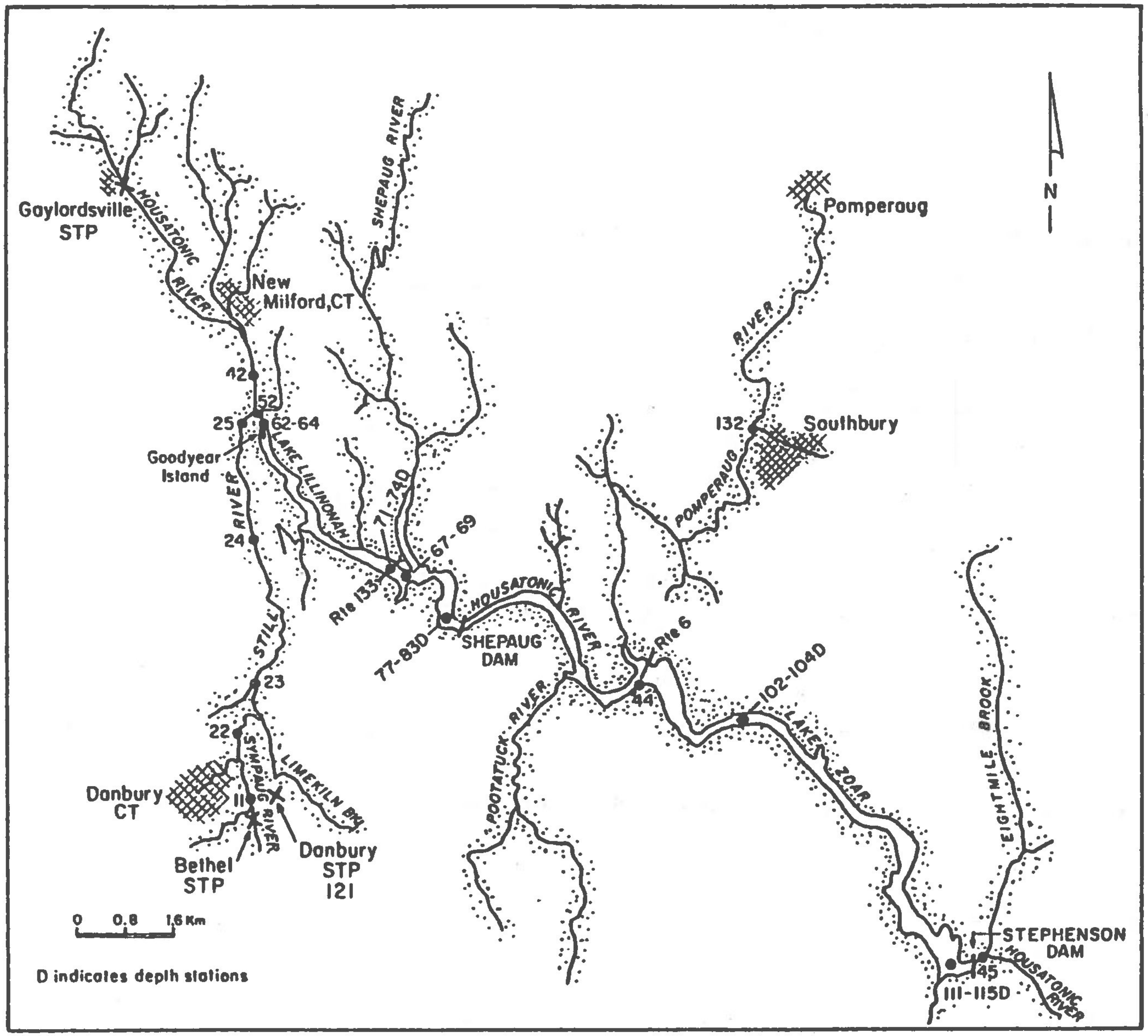


Figure 1. Study Area and Sampling Sites

(After Smith and Brown, 1978)

characteristics are presented in Table 1. This lake is generally considered to be highly eutrophic with frequent obnoxious blooms of blue-green algae occurring during the summer months. From data available, it appears that algal growth in the lake is generally phosphorus limited during that period. There is, however, some evidence for nitrogen or other limitation of algal growth at some times (State of Connecticut, 1975). Since the Danbury STP has been estimated to contribute 24-30 percent of the total phosphorus load to Lake Lillinonah (US EPA, 1975 and State of Connecticut, 1975, respectively), it is of interest to determine the impact of the P removal at the Danbury STP on the water quality in Lake Lillinonah.

The FMC Corporation conducted limnological surveys of Lake Lillinonah and Lake Zoar, an impoundment just downstream from Lake Lillinonah, and their major tributaries during the summers of 1976 and 1977. These surveys provided data that should be useful to evaluate the effect of phosphorus removal at the Danbury STP on water quality in Lakes Lillinonah and Zoar. Examination of these data shows that there was an apparent improvement in Lake Lillinonah water quality between the two years which could possibly be related to phosphorus removal at the Danbury STP. This was supported by statements made in the local popular press (Danbury News-Times September 18, 1977).

This paper presents an independent assessment of the results of the FMC study (Smith and Brown, 1978) employing some of the recently developed Vollenweider-OECD eutrophication modeling techniques to predict and evaluate changes in water quality that have occurred or would have been expected to occur as a result of altering the phosphorus load to the lake. The majority of this work considers the time period April 28 through September 30, because corresponding concentration and flow data were available for this period for both 1976 and 1977. Due to the complex system and insufficient data for some parameters, the water quality

TABLE 1
General Characteristics of Lake Lillinonah for Study Period June 1-September 15, 1976 and 1977

Characteristic	1976	1977
Mean Depth (m)*	11.9	11.9
Volume*		
m^3	9.13×10^7	9.13×10^7
acre-feet	74,000	74,000
Surface Area*		
m^2	7.69×10^6	7.69×10^6
acres	1,900	1,900
Mean Flow**		
m^3/sec	36.4	20.2
cfs	1,287	714
Hydraulic Residence Time*** (τ_ω) yrs	0.079	0.14

*US EPA (1975).

**Based on USGS (1976, 1977).

***Calculated as the quotient of the volume divided by the mean daily flow (June 1 - September 15).

in only Lake Lillinonah will be discussed. The impact of the phosphorus removal at Danbury would be expected to be greater in this lake than in Lake Zoar.

OECD EUTROPHICATION MODELING APPROACH

About five years ago, the Organization for Economic Cooperation and Development (OECD) initiated a eutrophication study program which had as its primary purpose, the formulation of algal nutrient load-lake and impoundment response relationships. This study is being conducted in western Europe, Japan, Australia, Canada, and the United States where a total of approximately 200 water bodies are being investigated. Within the US, the US EPA was the lead agency for the OECD eutrophication studies. Under contract with the US EPA, selected researchers compiled, using a standardized format, the results of their previous studies on approximately 40 US water bodies or parts thereof. These investigators prepared a series of reports which were submitted to the US EPA covering nutrient load-response relationships for their respective water bodies. These reports have recently been published (Seyb and Randolph, 1977). Rast and Lee (1978) prepared a summary report in which they critically examined each of the individual investigators' reports for their data reliability and comparability.

Rast and Lee (1978) found that the US OECD eutrophication study water bodies' nutrient load-response relationships can be formulated into relationships similar to those developed by Vollenweider (1975; 1976). Vollenweider found for a group of lakes, that the average summer chlorophyll a concentration was related to the phosphorus load normalized by mean depth and hydraulic residence time. Rast and Lee (1978) have shown that this relationship is applicable to a wide variety of US water bodies as well. They have also been able to extend

Vollenweider's relationship to include formulation of a P load-average summer Secchi depth relationship, and a P load-average hypolimnetic oxygen depletion rate relationship. Recently, Jones, Rast and Lee (Jones _et_ _al_., 1978) have extended this work and formulated a maximum summer chlorophyll _a_ concentration-average summer chlorophyll _a_ concentration relationship. Based on these efforts, it is now possible to predict, for many water bodies, the impact of altering a phosphorus load on the water quality of a lake or impoundment.

The Vollenweider-OECD eutrophication approaches provide the means to estimate the eutrophication response of a lake independent of its hydrologic characteristics. This is especially important in the case of Lake Lillinonah where the hydrologic characteristics of the Housatonic were markedly different during the two study periods. This in itself should have had a significant effect on water quality in Lake Lillinonah through an alteration of the hydraulic residence times of the lake. The modeling approaches applied here normalize the phosphorus loads so that the eutrophication response of Lillinonah to the altered Danbury STP load can be estimated.

CALCULATION OF PHOSPHORUS LOADS

In order to estimate the impact of removal of phosphorus from the Danbury STP effluent on the water quality in Lake Lillinonah, it is necessary to calculate the total P load to the lake as well as the percentage load from the Danbury STP. To do this, the input flows and concentrations must be determined.

It would appear from Figure 1 that the P concentrations and flows at Station 52 could be used to derive the total P load to Lake Lillinonah. One means of checking this estimated load would be to sum the loads at Stations 25 and 42 (Figure 1) and compare this load to that at Station 52. Although the Still River was, at one time, gaged at Station 25, it was not gaged during the study periods. According to Smith (1977), its flow is similar to that of the Pomperaug River which is located in the same geographic area and gaged at Southbury, Connecticut (Figure 1). The Pomeraug river flows were therefore, used where Still River flows were required. The Housatonic is gaged at Gaylordsville, Connecticut, about three miles upstream from Lake Lillinonah. These flows were used in calculating the P loads at Stations 42 and 52.

River Discharges

The mean daily discharges at the Gaylordsville and Southbury, Connecticut gaging stations for 1976 and 1977 were plotted over time (Figures 2 and 3). These figures indicate that the Still River makes a minor contribution to the flow of the Housatonic. Mean daily flows of the Housatonic River ranged from about 400 to over 10,000 cfs (11-280 m^3/sec), while that estimated for the Still River generally ranged from 5 to about 700 cfs (0.1-20 m^3/sec). At both gaging stations, during both years' studies, the discharges were highly variable, especially during the spring months. The flows were higher during the spring than in the summer. This could have had an effect on the water quality in the lake and is discussed further in a subsequent section.

The summer discharges in 1977 were markedly lower than in 1976 in both the Housatonic and Pomperaug Rivers (Figures 2 and 3). This is also demonstrated by the monthly rainfall patterns presented in Figure 4 (USGS 1976, 1977). For May, July, and August, not only was the 1977 rainfall considerably below that of 1976, but also was considerably below "normal".

Figure 5 presents a comparison of the mean monthly 1976 and 1977 discharges with the overall monthly discharges found for 1966-71 and 1975 (with one standard deviation of

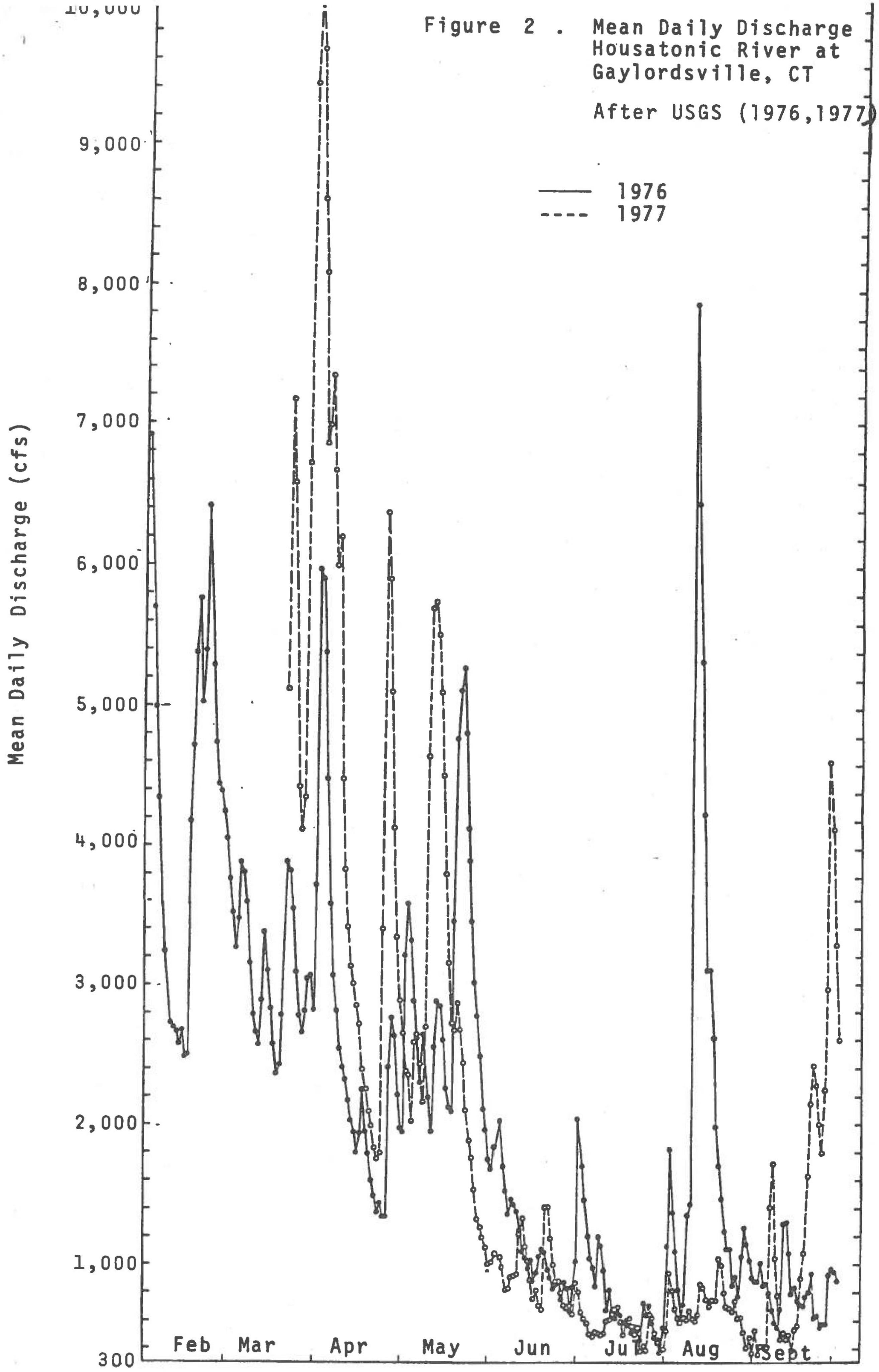


Figure 2 . Mean Daily Discharge Housatonic River at Gaylordsville, CT
After USGS (1976,1977)
1976
1977
Mean Daily Discharge (cfs)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
300
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept

Figure 3. Mean Daily Discharge - Pomeraug River at Southbury, CT.
After USGS (1976, 1977)

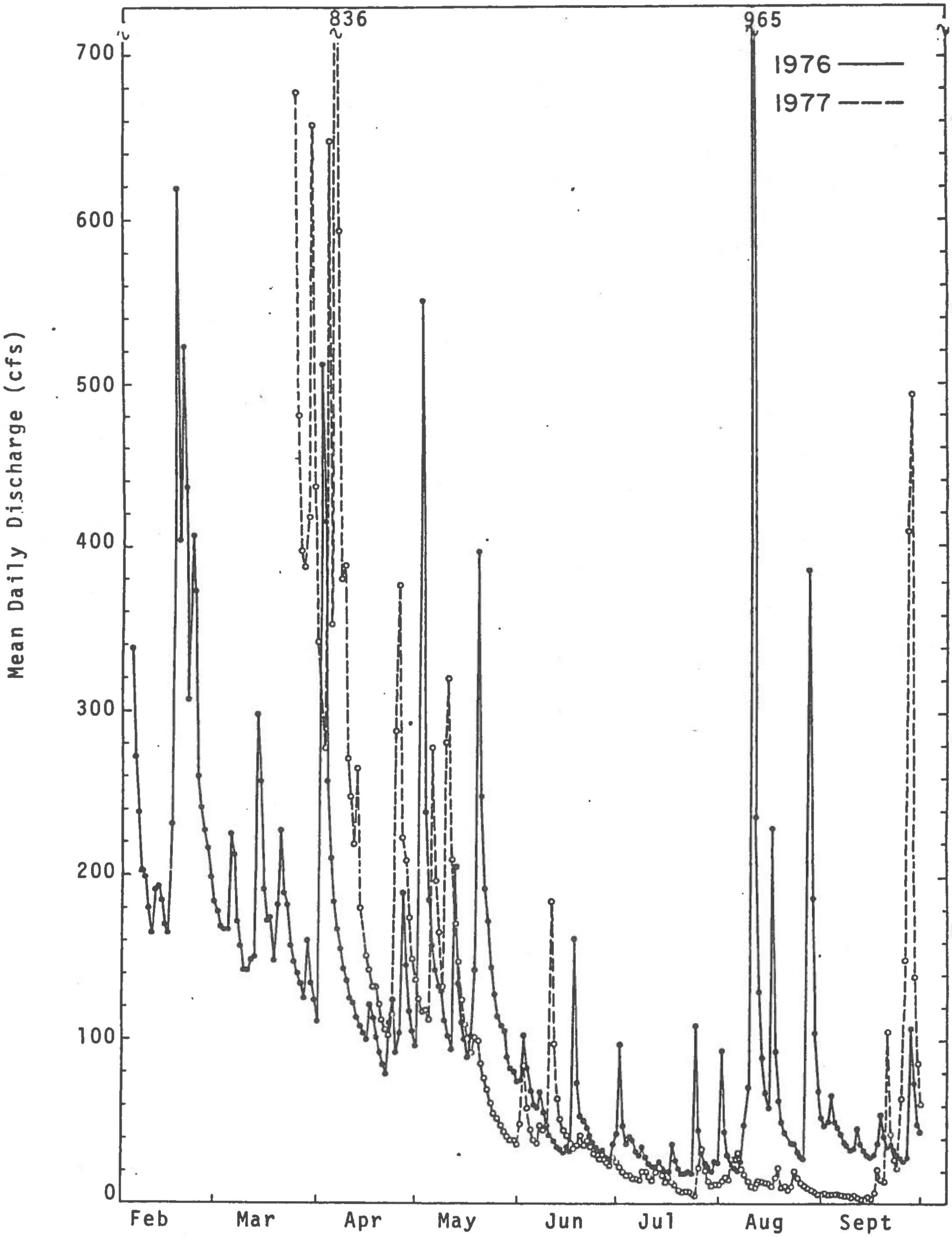
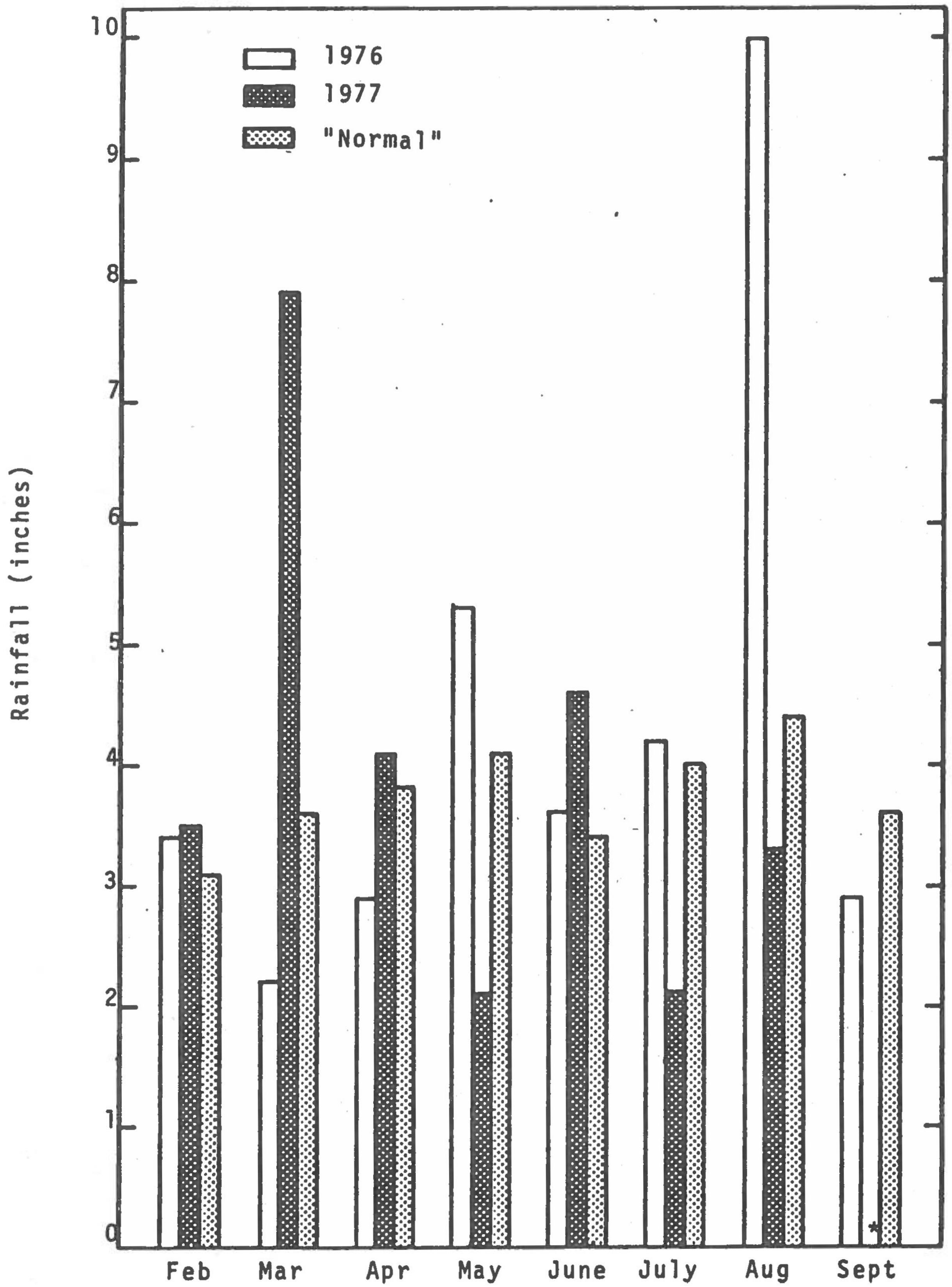


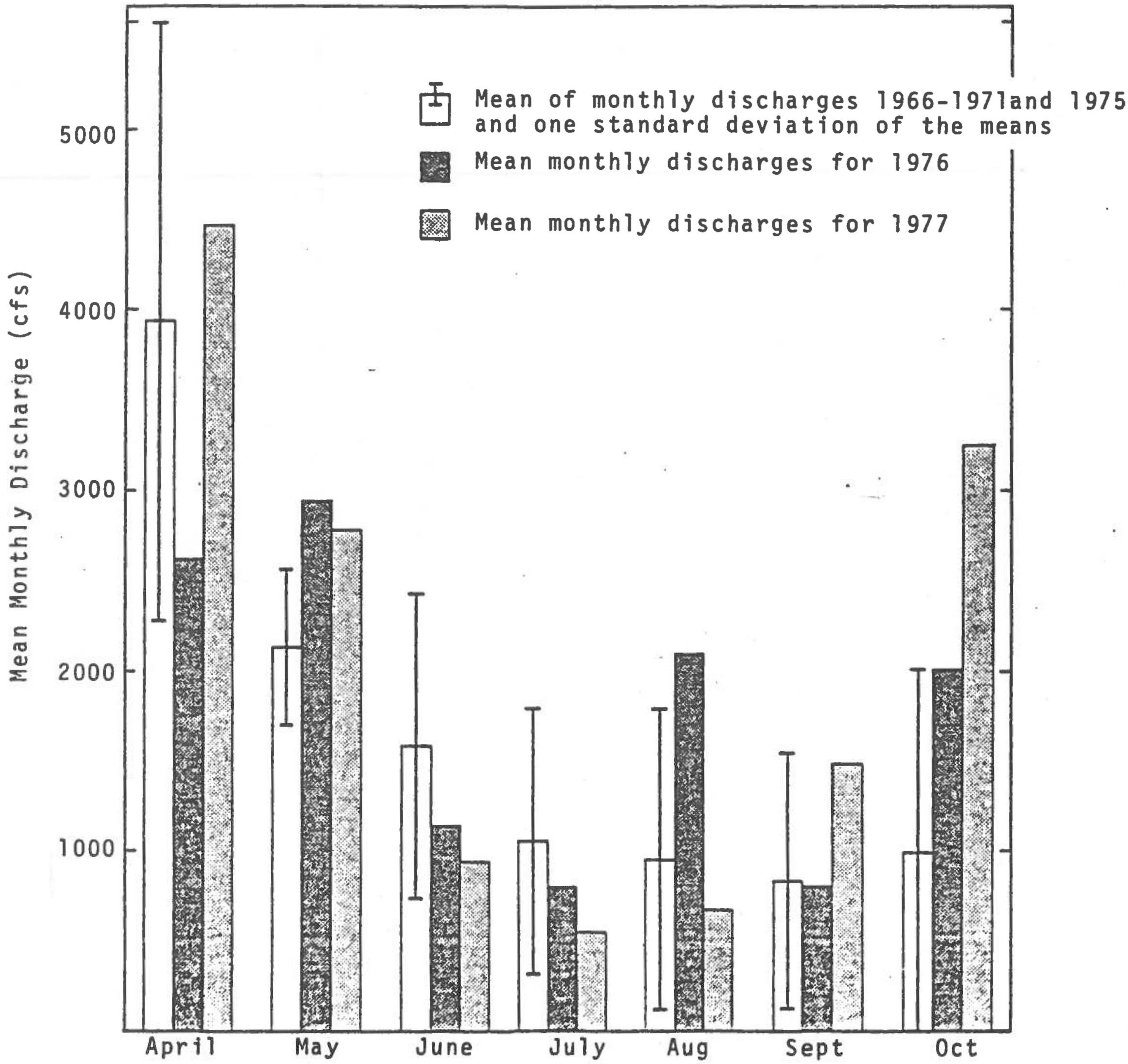
Figure 4 . Connecticut Rainfall

After USGS (1976, 1977)



*No data found

Figure 5. Mean Monthly Discharges of the Housatonic River
After USGS (1976, 1977)



the means). For the study period, it appears that the 1976 and 1977 flows are typically within one standard deviation of the overall mean found for previous years. May flows were higher than this average as was the August 1976 discharge.

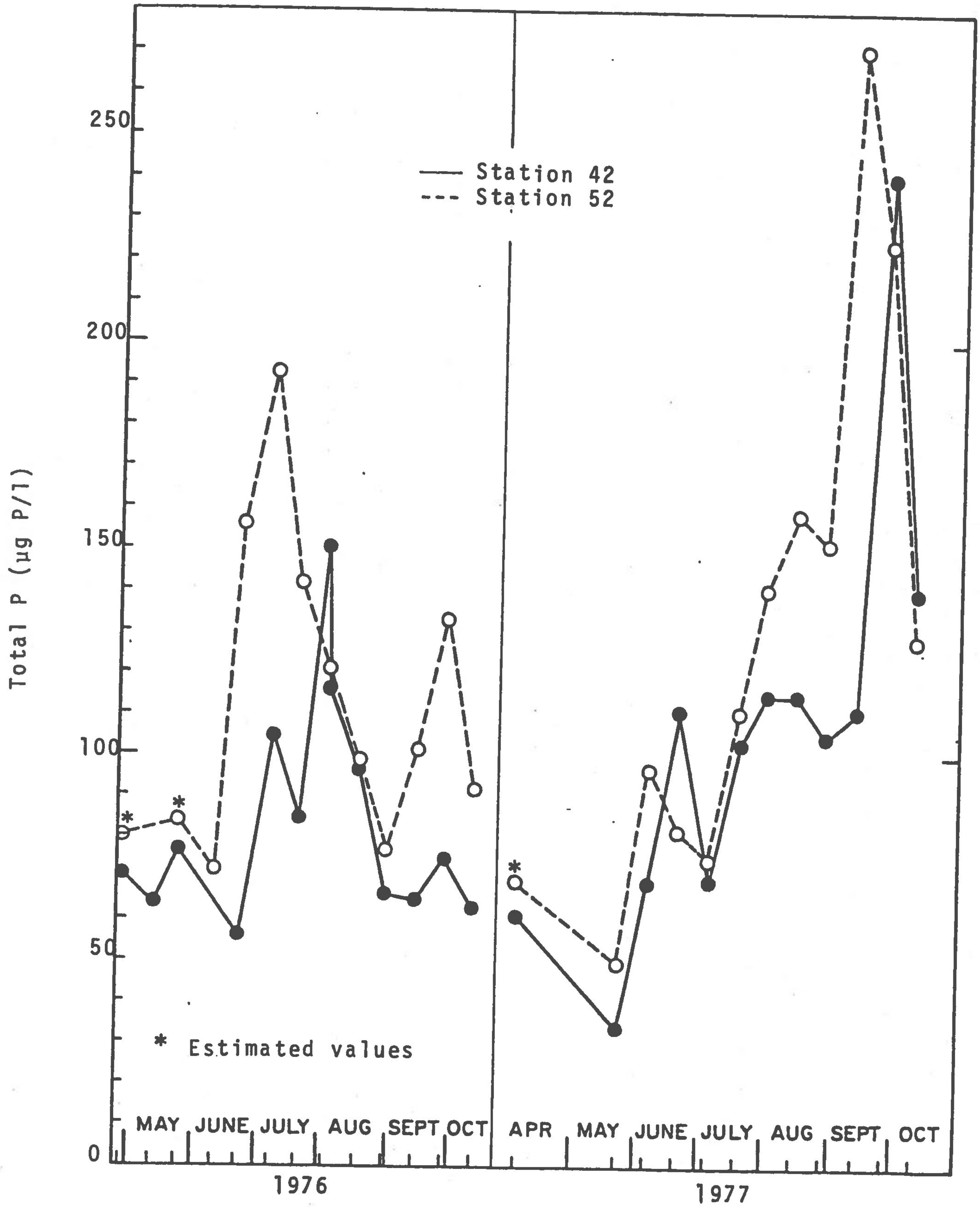
In mid-August 1976, there was a period of high flow in the Housatonic River (Figure 3). This high flow period yielded about 1.4×10^{10} cubic feet ($4 \times 10^{8} m^{3}$) of water, which was over four times the volume of Lake Lillinonah. The impact of this flow can be seen in the dissolved oxygen profiles in the lake (See Smith & Brown, 1978). At mid-lake, the water column profiles indicated that in early August 1976, before the high flow, the dissolved oxygen (DO) ranged from about 8.5 mg/l in the surface waters to about 2 mg/l between 8 and 11 m depth. At the Shepaug Dam, at the lower end of the lake, the DO ranged from about 8.5 mg/l at the surface to less than 1 mg/l below 7 m depth. During the high flow period, concentrations were increased throughout the water column at these locations; DO then appeared to remain in the bottom waters through the rest of the 1976 study. A similar situation occurred in mid to late August 1977 when the flows appeared to be somewhat elevated. This could have resulted from the increased flow of incoming water moving along the lake bottom increasing the DO content there. As seen at several in-lake stations, the high flow period during the summer of 1976 and, to a lesser extent, of 1977, appeared to result in a large influx of total phosphorus. This is also reflected in a large increase in chlorophyll <u>a</u> concentrations at a number of the in-lake stations, following the high flow periods (See Smith & Brown, 1978).

Phosphorus Loads

Since the flows were quite variable over time, it was inappropriate to use average tributary flow and average tributary concentrations for the study period in calculating the phosphorus loads at the various stations. Rather, daily loads should be calculated. In order to derive daily phosphorus concentrations at Stations 25, 42, and 52, the biweekly total P values were plotted over time; daily concentrations were then interpolated (Figures 6 and 7). In order to maintain the same study period for these stations for both years and, at the same time, include some of the spring flow characteristics, several values for concentrations at Station 52 were estimated by the authors. They were chosen to follow the relative patterns observed at the stations over the study period. The phosphorus load to Lake Lillinonah, based on the load at Station 52, was obtained by multiplying the interpolated, estimated, or measured total phosphorus concentration by the mean daily flow for each day during the study period (April 28-September 30). These daily values were summed to yield a total P load for the 156 day period. It was apparent from the short hydraulic residence times (the derivation of which is to be discussed) and the patterns of flow that the P load contributed during the spring and summer is the primary source of P which stimulates algal growth in the lake during the summer months. Phosphorus loads from fall, winter, and early spring would likely be flushed through the lake by late spring flows and, therefore, have little or no impact on summer algal growth. To account for this, and in light of the fact that the Vollenweider modeling approach requires yearly loads, the average daily load for the study period was assumed to be applicable for the entire year. The same method was used to calculate the P loads at Stations 25 and 42. The values for these loads are presented in Table 2.

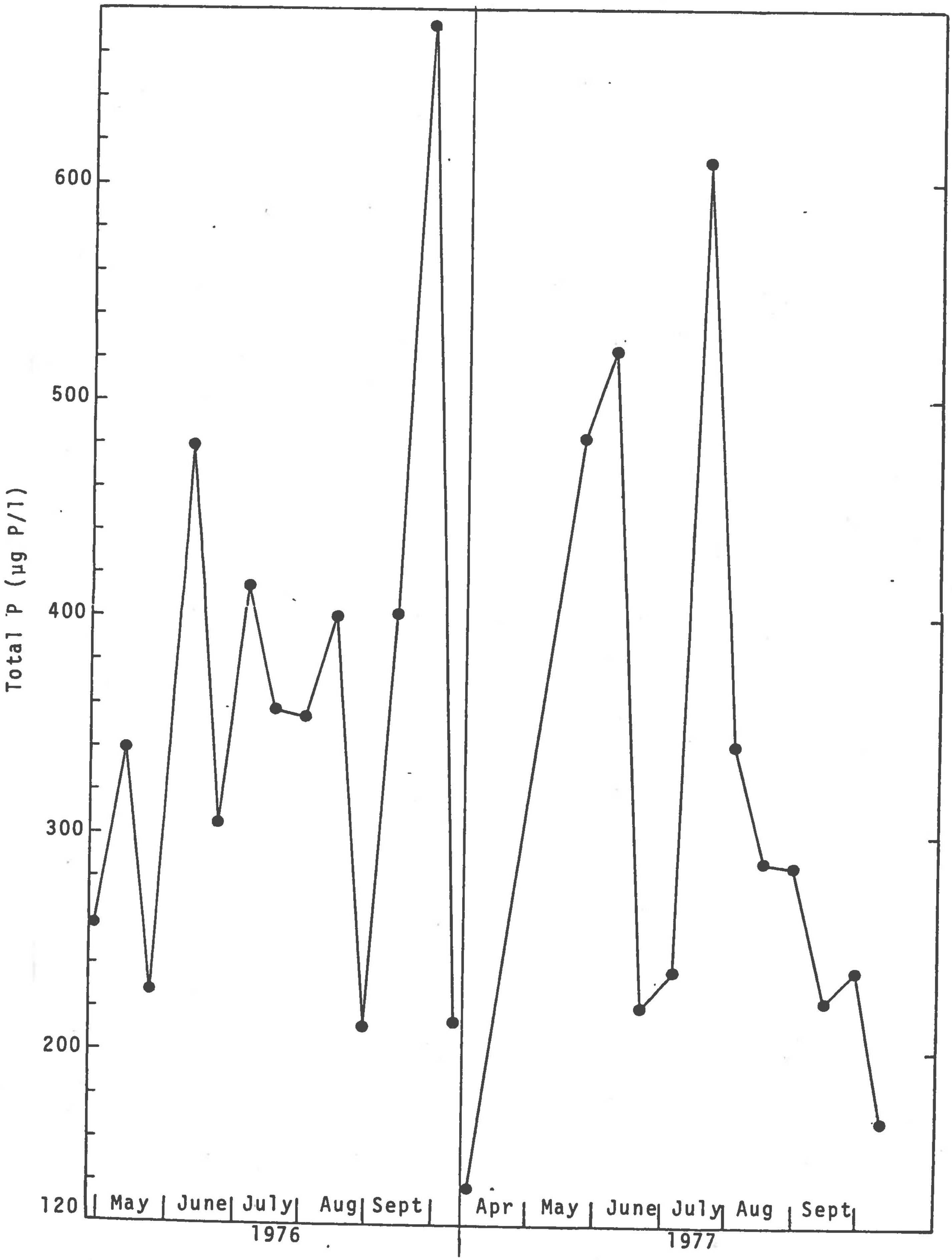
The mean monthly flows from the Danbury wastewater treatment plant for spring-summer 1976 and 1977 were made available to the authors by Cervera (1977). The biweekly values for the phosphorus concentration in the Danbury effluent, as measured as part of the FMC study, were used to calculate

Figure 6. Total Phosphorus Concentrations Over Time at Stations 42 and 52 - Housatonic River



After Smith and Brown, 1978.

Figure 7. Total Phosphorus Concentrations Over Time at Station 25 - Still River



After Smith and Brown, 1978.

TABLE 2

Summary of Total P Loads to Lake Lillinonah

Location	kg P/156 day (4/28-9/30)	
	1976	1977
Station 42	48,807	46,088
Station 52	61,798	56,865
Danbury STP	13,709	6,692
Station 25	10,282	7,102

monthly mean effluent P concentrations. By multiplying the mean monthly flow by the mean monthly P concentration by the number of days in the month, a monthly P load value was derived. The three days in April included in the study period, but for which there was no STP P data, were assumed to contribute the same load as was contributed in three days in May. A summary of these computations is presented in Table 3. As indicated by comparison of the monthly P load values for 1976 and 1977, after the Danbury STP P removal was initiated, there appeared to have been an average 70 percent reduction in total P load from the plant. The total loads from the Danbury plant are also included in Table 2 for comparison with other loads.

Examination of Table 2 shows that in 1976, there appears to have been a substantial removal of the total phosphorus from the Danbury wastewater treatment plant effluent in the Still River. Disregarding other loads to the river, more than 3,400 kg P were removed in the river between the Danbury STP outfall and Station 25 during the study period. Actual removal was likely much greater than this because of other inputs of phosphorus to that region of the river. The 1976 load from the Danbury STP effluent was about 22 percent of the Housatonic load at Station 52, whereas the Still was estimated to contribute about 17 percent of the Station 52 load.

Removal of some portion of total P load from the Danbury plant in the Still River during the 1977 study period cannot be demonstrated by the calculated loads at Station 25 and the Danbury effluent during the study period. It is likely, however, that some part of the Danbury P load was removed in the Still River in 1977 also. It may be expected that a greater amount of the total P load from the wastewater treatment plant would have been removed in the river during the

TABLE 3

Total Phosphorus Load from Danbury Wastewater Treatment Plant (April 28 - September 30)

Month	Mean Total P (µg P/l)	Mean Flow (mgd)	Mean P Load (kg P/day)	Total P Load for Month (kg P)
1976				
April*	3140	7.5	88	264
May	3140	7.5	88	2728
June	4298	7.1	116	3480
July	3211	6.2	74	2294
August	2870	7.7	83	2573
September	3142	6.6	79	2370
			Total P Load for Study Period	13709
1977				
April*	4405	6.12	101	303
May	4405	6.12	101	3131
June	1880	5.65	39	1170
July	1307	5.2	26	806
August	1232	4.8	22	682
September	1163	4.4	20	600
			Total P Load for Study Period	6692

*Daily load for the three days in April included in this study period were assumed to be the same as the mean daily load in May.

Based on Smith and Brown (1978) and Cervera (1977).

summer of 1977 because of the apparently markedly lower flow than in 1977 than in 1976.

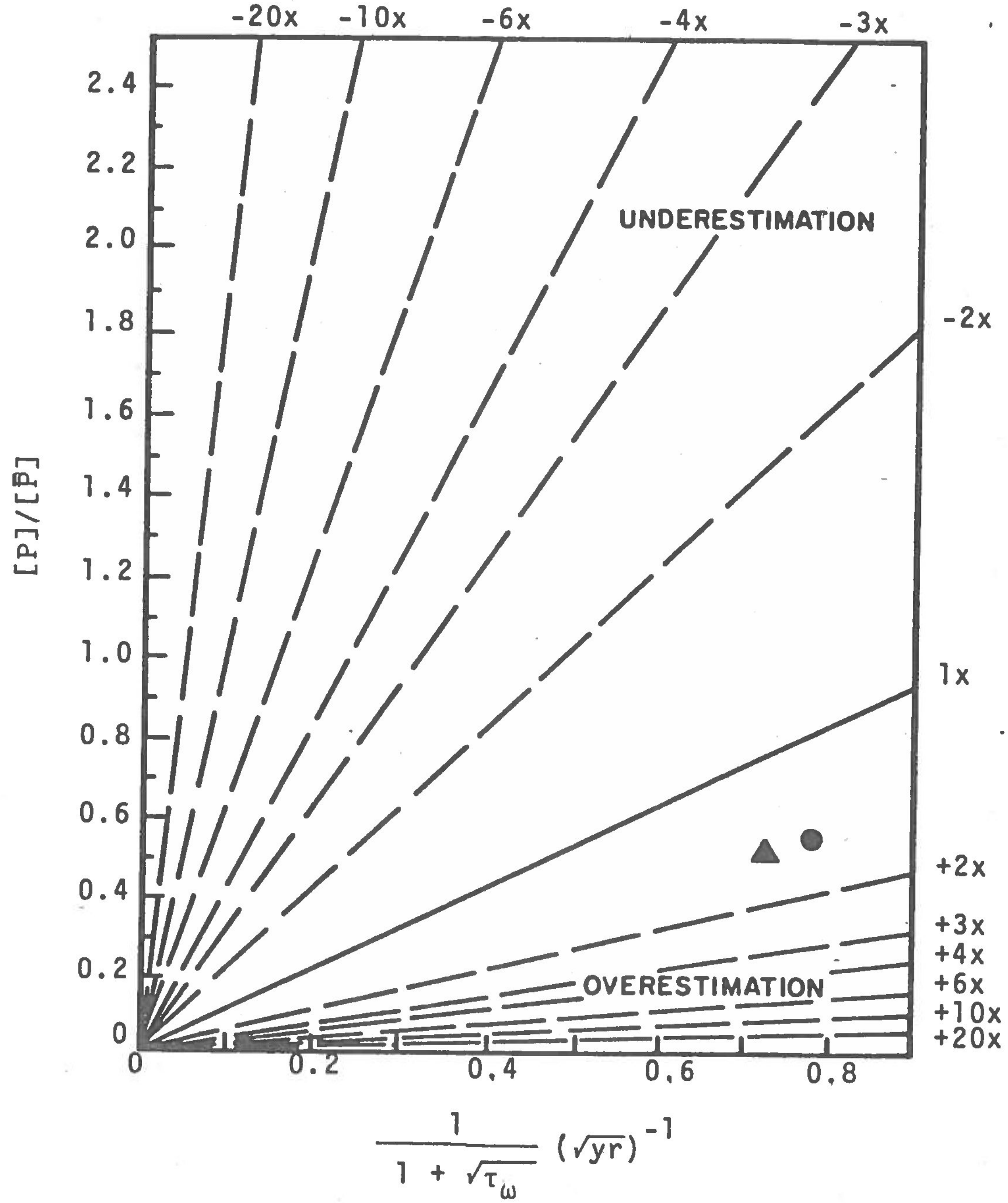
A comparison of the load calculated using Station 52 values with that calculated using the sum of values at Stations 25 and 42 shows that, based on the sampling program used and the discharge information available, there is reasonable agreement of these load estimates. For the purpose of nutrient load-response relationship development, the phosphorus load, as calculated for Station 52, was used for the load to Lake Lillinonah.

EVALUATION OF LOADING ESTIMATES

In order to determine if the loads calculated for Lake Lillinonah were reasonable with reference to how lake systems have been found to typically behave, the 1976 and 1977 P loads were plotted on a Vollenweider mean phosphorus/influent phosphorus-mean depth/hydraulic residence time diagram (Figure 8). Table 4 presents the values from which these points were plotted. The mean phosphorus concentration [P] in the lake was determined by taking the arithmetic mean of the measured biweekly phosphorus concentrations at all stations in the lake (Smith and Brown, 1978). (Obviously erroneous data were excluded.) Influent phosphorus concentrations were derived by dividing the arithmetic mean of the concentrations at Station 52 by the mean daily flow into the lake as measured on the Housatonic for the 156-day study period.

By dividing the lake volume, which was assumed to be constant, by the mean inflow during the period June 1 - September 15, the hydraulic residence time (τ_{ω}) was determined. This time period (June 1 - September 15) was used for calculation of the hydraulic residence time because the hydraulic residence time during this period is the one which is applicable to algal growth during the time of greatest recreational use of the water body. Algal growth, however, is influenced by the P

Figure 8. Evaluation of Estimates of Lake Lillinonah Phosphorus Loadings: Vollenweider Mean Phosphorus/ Influent Phosphorus and Hydraulic Residence Time Relationship



● 1976 load calculated using Station 52 P loads

▲ 1977 load calculated using Station 52 P loads

TABLE 4

Evaluation of Loading Estimates

Parameter	1976	1977
P load (kg P/day)*	397	364
[P] (μg P/l)	65	68
[$\bar{P}$] (μg P/l)	119	136
τ_ω (yr)**	0.079	0.14

[P] = mean total P concentration in the lake (excluding unrealistic values). (April 28 - September 30)

[$\bar{P}$] = mean influent total P concentration.(April 28 - September 30)

τ_ω = hydraulic residence time.

Dash (-) indicates not measured for calculations.

*Based on period April 28-September 30).

**Based on period June 1-September 15.

load entering the lake in the late spring as well as that entering during the summer. The residence time was about 29 days in the summer of 1976 and about 51 days in the summer of 1977.

The "1x" line on the diagram (Figure 8) indicates where a lake with a given hydraulic residence time should theoretically plot. It was found by Rast and Lee (1978) that for a lake which plotted within $\pm$ 2 times the $[P]/[\bar{P}]$, the P load has been estimated with an acceptable degree of accuracy. This finding was based on the fact that a large number of water bodies obey this Vollenweider relationship and typically fall within a factor of two of the "1x" line. Figure 8 shows that the Station 52 total P load gives a reasonable estimate of the total phosphorus load to Lake Lillinonah.

PHOSPHORUS LOADING DIAGRAM

The general, physical and chemical characteristics of Lake Lillinonah needed to plot this lake on the Vollenweider phosphorus loading curve are presented in Table 5. The position of Lake Lillinonah on the Vollenweider phosphorus loading curve (Figure 9) was determined for each of the following loading and hydrologic conditions: 1) 1976 P load and hydraulic residence time; 2) 1976 Housatonic P load with only 15 percent of the Danbury STP P load, i.e., 85 percent of the Danbury STP load, a percent removable which is readily achievable, was subtracted from the Station 52 load; 3) 1976 Housatonic P load with only 30 percent of the Danbury STP load; 4) 1977 P load and the hydraulic residence time; 5) 1977 P load substituting the 1976 load from the Danbury STP for the 1977 Danbury STP load; and 6) 1977 P load substituting the 1976 Danbury STP P loads for those months (June - September) when some phosphorus was being removed at the Danbury treatment plant. Figure 9 shows that for both 1976 and 1977, Lake Lillinonah plots above the "excessive loading" line, in the area where many lakes

TABLE 5

Characteristics of Lake Lillinonah for Eutrophication Modeling

Parameter	1976	1976a	1976b	1977	1977a	1977b
Mean Depth, $\bar{z}$ (m)	11.9	11.9	11.9	11.9	11.9	11.9
Hydraulic Residence Time, τ_{ω} (yrs)**	0.079	0.079	0.079	0.14	0.14	0.14
Areal P Loads, L(P) ($g/m^2/yr$)***	18.9	15.3	15.9	17.3	19.4	19.6
Mean Summer in-lake Chlorophyll a (μg/l)**	34.6	29*	30*	32.6	36*	36.2*
Mean Summer Secchi Depth (m)	1.1	1.2*	1.2*	1.6	1.5*	1.5*

1976a = 1976 flow characteristics; 85 percent of Danbury STP P load subtracted from load to lake.

1976b = 1976 flow characteristics; 70 percent of Danbury STP P load subtracted from load to lake.

1977a = 1977 flow characteristics; 1976 load from Danbury STP used instead of 1977 load.

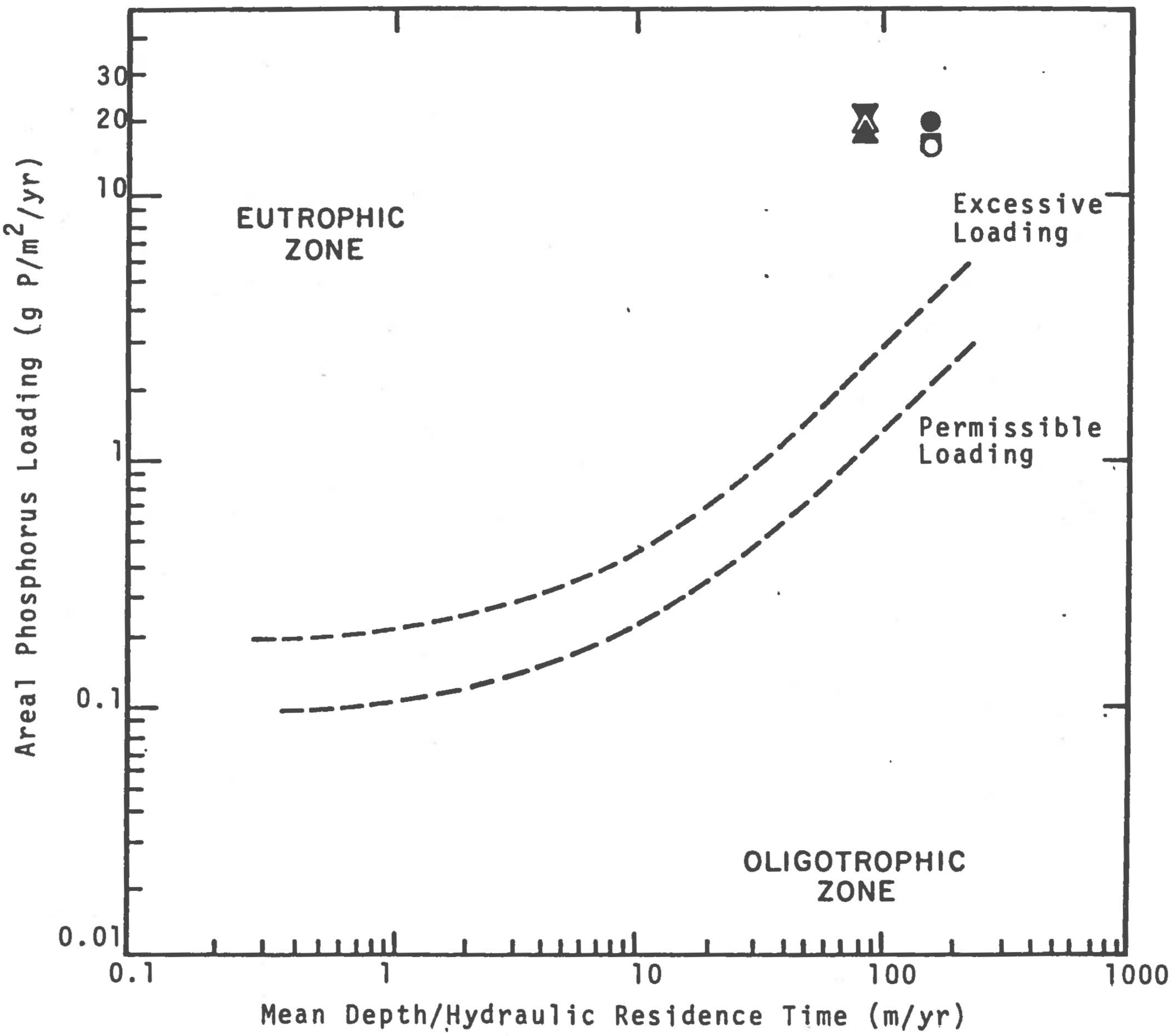
1977b = 1977 load using 1976 Danbury STP loads for June-September only.

* = Values predicted by model.

** = Based on data from June 1 - September 15.

*** = Based on data from April 28 - September 30.

Figure 9. Vollenweider Phosphorus Loading Curve - Summers 1976 and 1977



● - 1976 P load
○ - 1976 P load less 85% of Danbury STP P load
■ - 1976 P load less 70% of Danbury STP P load
▲ - 1977 P load
△ - 1977 P load with 1976 Danbury STP P load
▼ - 1977 P load with 1976 Danbury STP P load for June-Sept

classified as eutrophic plot. It also shows that a dramatic change in water quality as a result of initiation of phosphorus removal at the Danbury treatment plant would not be expected. As discussed by Rast and Lee (1978) water quality is related to the vertical distance above the permissible loading line. Those lakes which plot at the greatest vertical distance above the line would have the poorest water quality. In order to interpret the differences in phosphorus load shown in Figure 9, it is necessary to utilize the approach developed by Vollenweider and evaluated by Rast and Lee (1978) of relating phosphorus load to mean summer chlorophyll a concentrations.

MODELING LAKE WATER QUALITY RESPONSE TO ALTERED P LOAD

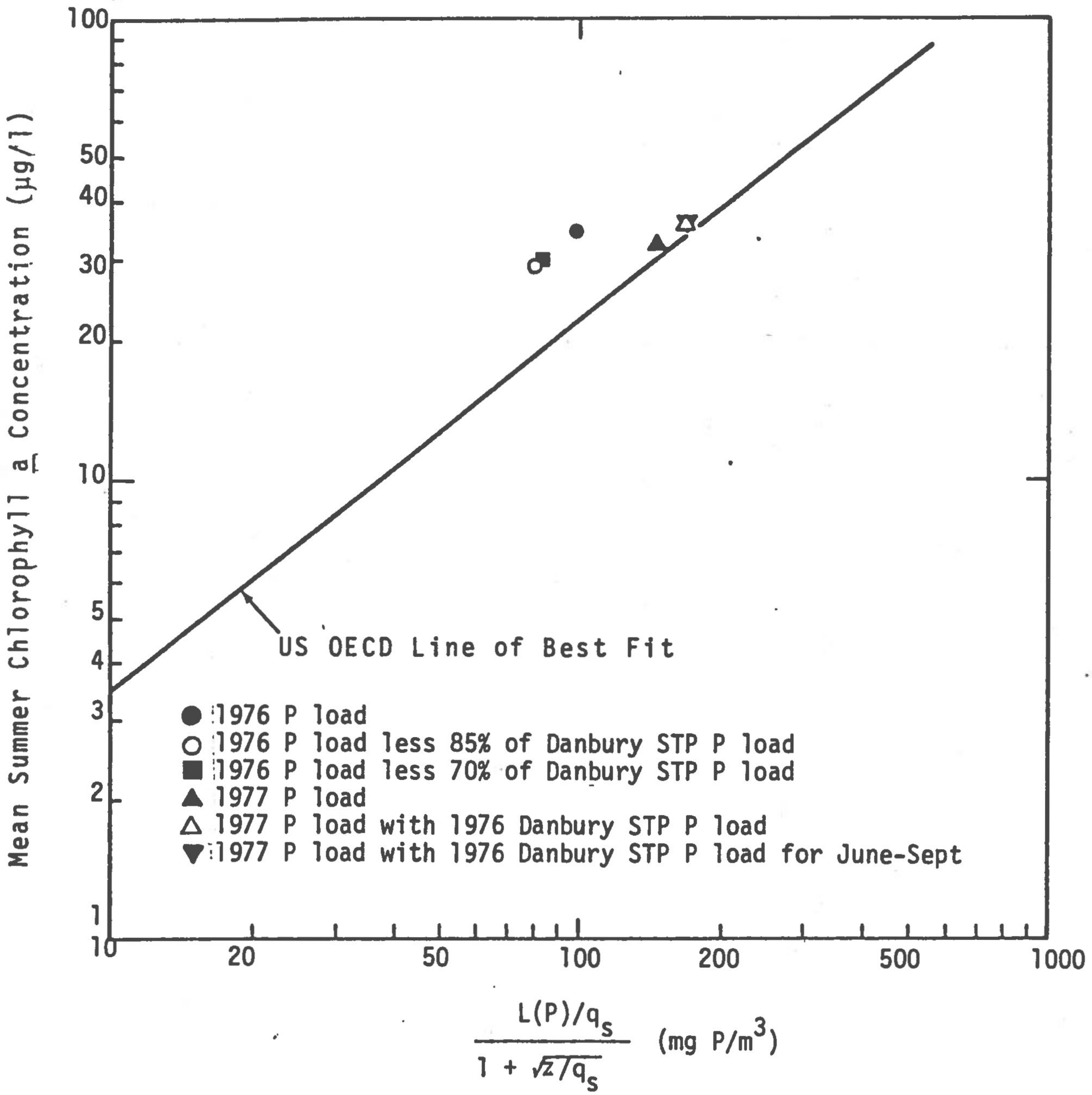
Based on their work on about 40 US OECD water bodies, Rast and Lee (1978) have defined a relationship between the mean summer chlorophyll a concentration in a lake in which planktonic algal growth is P limited, and the P load to the lake normalized by the lake's mean depth and hydraulic residence time. This relationship and approach allow the mean summer chlorophyll a concentration of a lake to be predicted based on the lake's phosphorus load, mean depth, and hydraulic residence time. They also can be used to predict the change in water quality, as measured by mean summer chlorophyll a concentration, that would be expected to result from altered P load or hydraulic residence time. It has been repeatedly demonstrated that this approach can be applied to many lakes throughout the world.

In order to use this approach for Lake Lillinonah, a mean summer chlorophyll a concentration must be determined. In the FMC study, chlorophyll a concentrations were determined for the lake surface waters at about biweekly intervals between June and October in both 1976 and 1977 (Smith and Brown, 1978). Eight stations were monitored in 1976; four in 1977.
Since the period of concern with respect to water quality in

Lake Lillinonah is the summer months when the lake is used for recreation, chlorophyll a values during the period early or mid-June to mid-September were used in modeling changes in water quality. There were several unrealistically high chlorophyll a values (ranging from about 150-900 µg/l) reported for several samples by Smith and Brown (1978). These values likely resulted from the analysis of a scum of algae on the lake surface, and were excluded when the arithmetic mean of the chlorophyll a concentrations were taken. Justification for this approach stems from the fact that the algal scum is not representative of living algal growth; it is generally composed of dead or dying algal cells which accumulate in areas of a lake depending on wind direction and speed. These scums usually last only a short time. It is not generally understood by those in the water quality field how to use, in a meaningful way, the results of such analyses on surface algal scum, in assessing water quality. The arithmetic mean of the summer chlorophyll a concentrations in surface (1 m) waters, excluding those of the algal scum, was used as the mean summer chlorophyll a concentration.

Table 5 presents the P loading and lake characteristics necessary to apply the Rast and Lee chlorophyll a - P load relationship to Lake Lillinonah under the various loading and hydraulic conditions given or assumed. Figure 10 shows the positions of the lake in 1976 and 1977, relative to the US OECD line of best fit for this relationship and also expected changes in the mean summer chlorophyll a concentration resulting from altered P loads. This figure shows that for both 1976 and 1977, the relationship for Lake Lillinonah is very similar to that determined for other water bodies having the same P load - mean depth/hydraulic residence time characteristics, i.e., the lake plots near the US OECD line of best fit. This finding gives considerable support to the validity of the assumptions made

Figure 10. Relationship Between Phosphorus Load and Mean Summer Chlorophyll a Concentrations in Lake Lillinonah



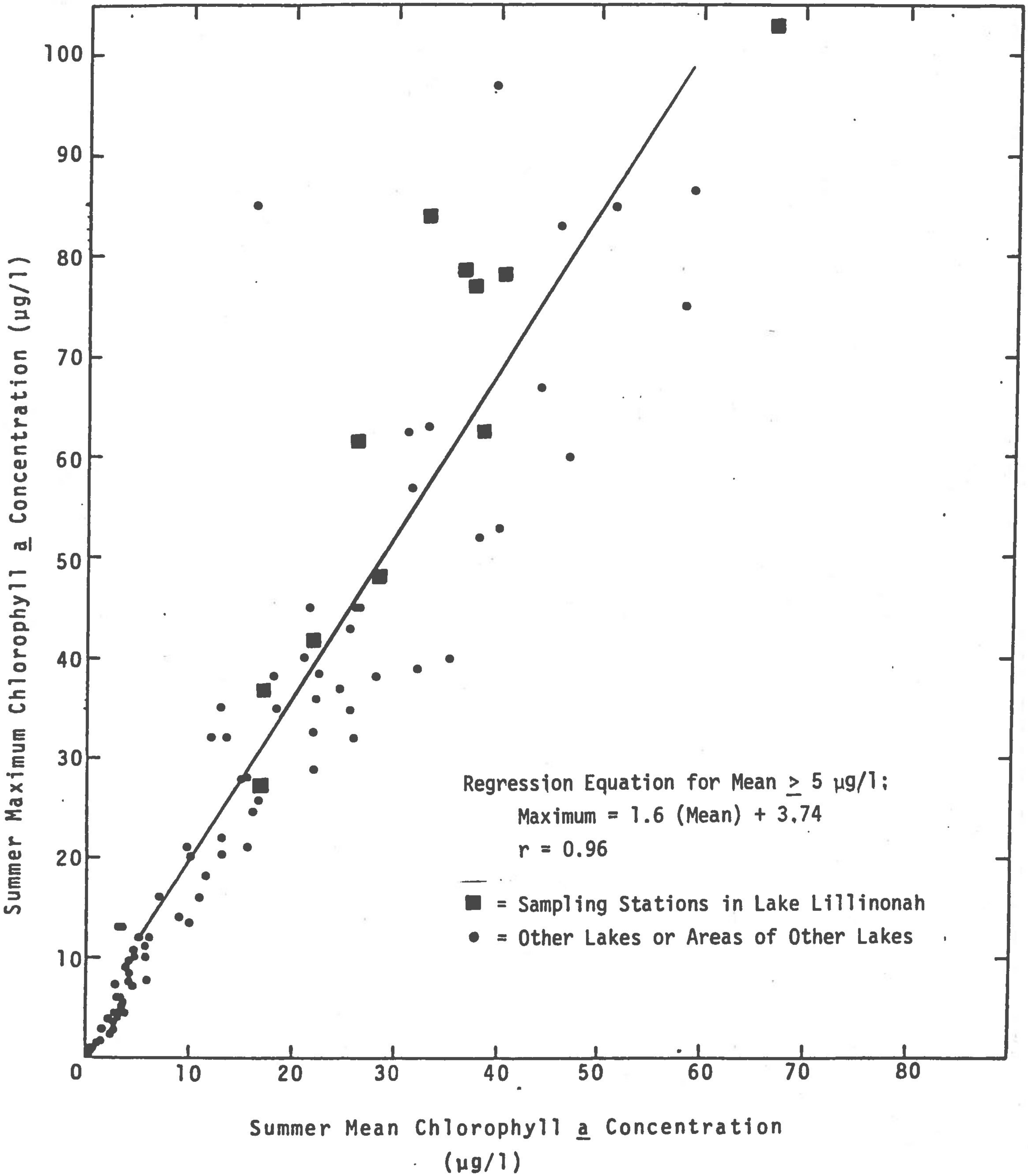
with respect to the characteristics of the lake that were used to evaluate nutrient load-response relationships.

Figure 10 shows that there was a reduction in the mean summer chlorophyll a concentration between 1976 and 1977. Further, it predicts that had thetotal phosphorus load to the lake been reduced in 1976 by an amount equivalent to 70 to 85 percent of the Danbury wastewater treatment plant P load, a reduction in the mean summer chlorophyll a concentrations would have been from approximately 35 μg/l (actually found in 1976) to 29-30 μg/l. This model also predicted that if the 70 percent of the Danbury STP P load that had apparently been removed at the plant had not been removed in 1977, the mean summer chlorophyll a concentration would have increased from about 35 μg/l in 1976 to approximately 36 μg/l in 1977 (See Table 5). It is, however, generally the maximum levels or the total "greenness" of the water to which the public responds. While the Vollenweider model is applicable to mean summer chlorophyll a concentrations, there is a linear relationship between mean summer chlorophyll a and the summer maximum values (Jones, Rast, and Lee, 1978). Figure 11 shows this relationship for 62 areas of 20 lakes around the US, including the Lake Lillinonah sampling stations. Points for Lake Lillinonah were determined by determining the arithmetic means of the approximately biweekly, 1 meter chlorophyll a values at each station for the period June to mid-September and plotting them against the maximum concentration (excluding the unrealistically high values) found at each respective station for that period. As presented in Figure 11, the regression equation is:

Maximum Summer Chlorophyll a Concentration =
1.6 (Mean Summer Chlorophyll a Concentration) + 3.74

with an r of 0.96. The authors have developed a general relationship that relates the maximum summer chlorophyll a concentration to the phosphorus load to a lake in which planktonic algal growth is limited by phosphorus.

Figure 11. Relationship between Mean Summer Chlorophyll a and Maximum Summer Chlorophyll a Concentrations (After Jones, Rast, and Lee, 1978)



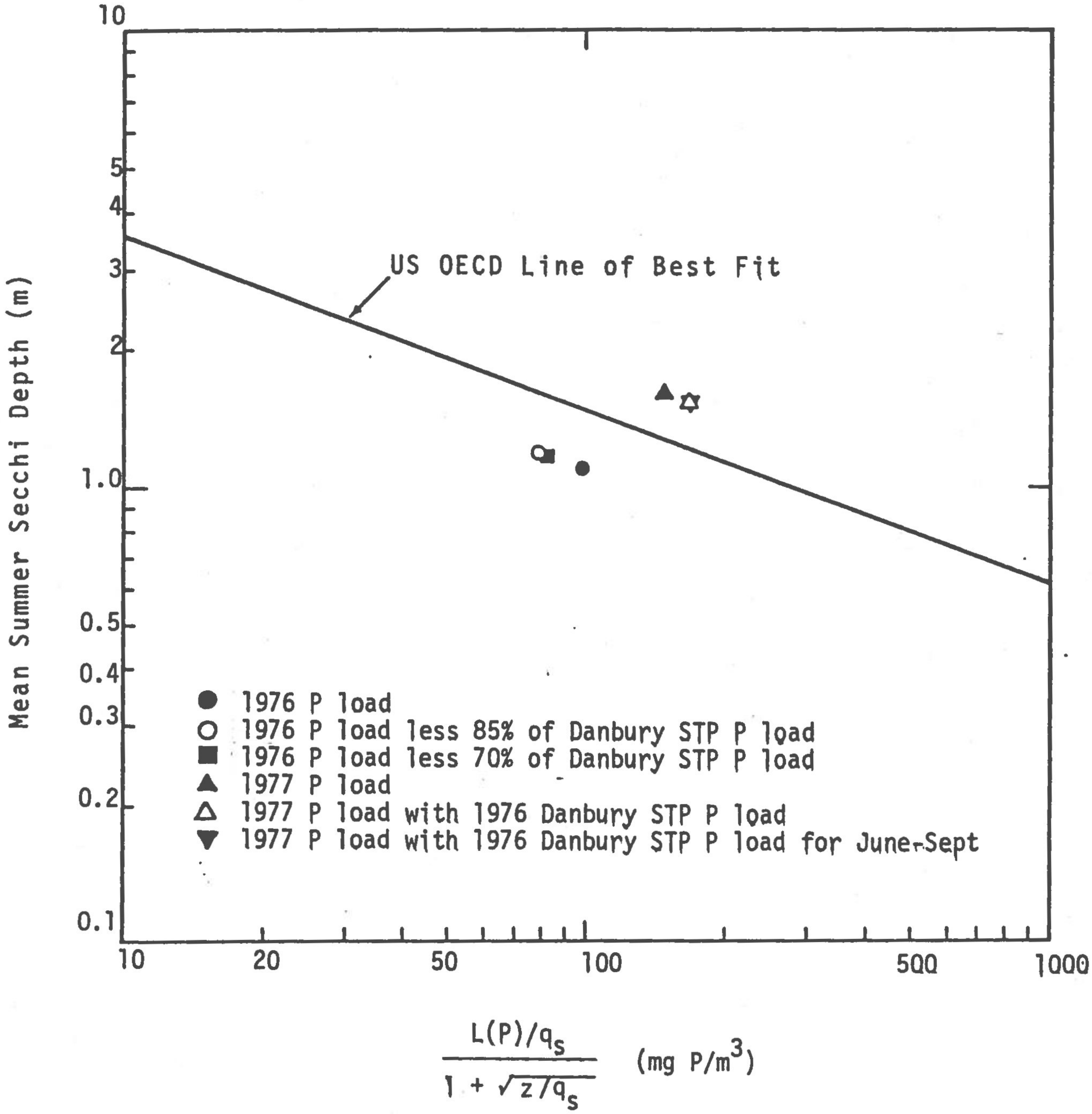
SECCHI DEPTH - PHOSPHORUS LOAD RELATIONSHIP

Rast and Lee (1978) developed a relationship and approach for mean summer Secchi depth in lakes in which the planktonic algal growth is P limited, similar to that developed for chlorophyll a. Although Secchi depth is generally a less sensitive water quality parameter than chlorophyll for moderately eutrophic to eutrophic water bodies, this relationship and the predictive capabilities of this model have been demonstrated for a wide variety of lakes.

As part of the FMC study, Secchi depth was generally measured in Lake Lillinonah at approximately biweekly intervals during the summers (mid-June to mid-September) of 1976 and 1977 (Smith and Brown, 1978). Eight lake stations were monitored in 1976; four in 1977. Those values corresponding to the unrealistically high chlorophyll a values were excluded from the averaging since values for Secchi depth, when determined under conditions of surface algal scum, are not interpretable. Since light penetration in water is a logarithmic function, the arithmetic mean of the logs of the individual Secchi depth values was taken by the authors; the antilog of this mean was then used as the mean summer Secchi depth in this modeling. Table 5 presents the mean summer Secchi depths for 1976 and 1977 as well as those predicted for various alterations of P load, based on the Rast and Lee model.

Figure 12 shows the positions that Lake Lillinonah assumes in 1976 and 1977 relative to the US OECD line of best fit for the Secchi depth-P load relationship. The lake, in both 1976 and 1977, appears to have a relationship between mean summer Secchi depth and P load normalized by mean depth and hydraulic residence time similar to that found by Rast and Lee (1978) for many US water bodies. This model predicted that if the P load to the lake was reduced in 1976 by an amount equivalent to the removal of 70-85 percent of the Danbury P load, the mean summer

Figure 12. Relationship between Phosphorus Load and Mean Summer Secchi Depth for Lake Lillinonah



Secchi depth would have increased by 0.1 m to 1.2 m (See Table 5). If the proportion of the Danbury P load that can be estimated to have been removed as a result of Danbury's advanced wastewater treatment, were added to the 1977 phosphorus load to the lake, the model predicted that the mean summer (1977) Secchi depth would have been 1.5 m.

DISCUSSION

The US EPA National Eutrophication Survey report on Lake Lillinonah indicated that the Vollenweider nutrient load-lake response relationship may not be applicable to this lake because of its short hydraulic residence time. An important conclusion from this study is, however, that the Vollenweider P load-chlorophyll relationship can be applied to water bodies with short annual hydraulic residence times provided that during the period of maximum chlorophyll production there is adequate time for phytoplankton to utilize the available phosphorus in the water body.

It is evident from examination of the results of this study that the improved water quality in Lake Lillinonah that was found in 1977 compared to 1976 can be attributed at least in part to the removal of phosphorus by chemical precipitation at the Danbury sewage treatment plant. When one adjusts the 1977 P load data for the expected impact of flow on water quality, i.e., assuming that the Danbury P load from one year is applicable to the other year, it is found that Lake Lillinonah should have had slightly worse water quality in 1977 than was experienced in 1976 had there been no P removal at the Danbury STP in 1977. Therefore, it appears that the phosphorus removal at the Danbury STP overcame the impact of the different flows for the two years. The results of this study support the results of Smith and Brown (1978) that phosphorus removal should be continued at the Danbury STP. Upstream phosphorus sources such as the Pittsfield, Massachusetts STP should be critically examined to determine the potential improvement in Lake Lillinonah water quality that could result from chemical treatment for P removal. From a preliminary point of view, it appears that initiation of chemical treatment for phosphorus removal at Danbury, Connecticut; Pittsfield, Massachusetts; or other communities which discharge wastewaters into the Housatonic River or its tributaries above Lake Lillinonah, could result in a significant improvement in water quality in this lake.

One of the important observations from this study is that phosphorus removal based on a detergent phosphate ban would likely have very limited impact on water quality in Lake Lillinonah. As noted earlier, about 35 percent of the phosphorus in domestic wastewaters can be attributed to the use of phosphate as a builder in synthetic detergents. Therefore, the maximum removal of phosphorus that could be achieved at the Danbury STP by a detergent phosphate ban, would be on the order of half of that actually achieved during the summer of 1977. Actually, it is expected that with extended experience and good maintenance and operation practices, upwards of 90 percent removal of the phosphorus in the Danbury domestic wastewaters can be achieved using chemical precipitation procedures. Therefore, even greater reductions in the mean and maximum summer chlorophyll concentrations in Lake Lillinonah would be expected in the future as a result of phosphorus removal from domestic wastewaters by chemical precipitation.

It should also be noted that in addition to providing phosphorus removal at a small cost (less than one cent per person per day for the population served (Smith and Brown, 1978)), other benefits such as further removal of BOD, suspended solids, heavy metals and trace organics, would be expected concommitant with P removal by chemical precipitation.

Results of this study support the proposal of Smith and Brown (1978) of removing P only during the late spring and summer. It does not appear that there is a need to practice P removal during fall, winter, and early spring since P contributed to Lake Lillinonah during this period is likely flushed through the lake during high flows in the early spring. This practice would further reduce the cost of P removal by chemical precipitation at the treatment plants that discharge to the Housatonic or one of its tributaries above Lake Lillinonah.

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