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Effects of wastewater diversion on the lower Madison lakes

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THE MADISON, Wis., lakes, which are among the most studied lakes in the world, are of particular interest with regard to their response to a reduced nutrient loading resulting from diversion of wastewater effluent. Although there have been several diversions in the history of these lakes,[1-3] the most significant diversion occurred in December 1958, when treated wastewater from metropolitan Madison was diverted from entering the two lower Madison lakes. Because it has been about 15 yr since this diversion took place, the opportunity exists to observe the long-term effects of the diversion, particularly with regard to the phosphorus content of the lakes.

The lower Madison lakes, Lake Waubesa and Lake Kegonsa, are part of a chain of lakes along the Yahara River, as shown in Figure 1. The currently sewered area of metropolitan Madison and the scheme of flow of treated wastewater are also shown. The lower lakes drain an area composed mostly of rural farm land and residential areas. Waubesa is the smallest of the Yahara lake chain, and Kegonsa is the second smallest. Both lakes are quite shallow and are generally well mixed during most of the year. Pertinent physical characteristics of all the Madison lakes are summarized in Table I.

In 1938, the Nine Springs Treatment Plant began discharging its effluent into the Yahara River above Lake Waubesa (Figure 1), and the lake immediately began to show the effects of increased nutrient enrichment. Chemical treatment was practiced to control the severe nuisance of algal blooms and aquatic weeds that developed in both Waubesa and Kegonsa.

As a consequence of the public's displeasure over the condition of Lake Waubesa and Lake Kegonsa and the denial by some individuals that wastewater was a factor in stimulating algal growth, a detailed study of the sources of nutrients was undertaken. The study, under the direction of C. N. Sawyer, was unique in that, for the first time, a detailed nutrient budget was determined by measuring the amounts of nutrients entering a lake from various sources. Sawyer *et al.*[4, 5] found that 88 percent of the inorganic phosphorus loading received by Lake Waubesa came from the Nine Springs Plant effluent. Furthermore, they reported that 97 percent of the phosphorus input to Lake Kegonsa came from Lake Waubesa via the Yahara River. The studies of Sawyer *et al.* were followed by a series of hydrologic and chemical investigations of the Madison lakes by a variety of researchers at the University of Wisconsin. These studies clearly demonstrated that wastewater was a major source of aquatic plant nutrients (such as phosphorus) for Lake Waubesa and, ultimately, for Lake Kegonsa.

Finally, after much public debate and community bickering, it was decided that Madison's treated wastewater effluent should be completely diverted around the lower lakes. In December 1958, this diversion was completed, and effluent from the Nine Springs Plant is now discharged into the lower Yahara River, around all of the Madison lakes, via Badfish Creek (Figure 1).

In an endeavor to evaluate the effects of the diversion on the lower lakes, a biological and chemical study was initiated in June 1959 by researchers at the University of Wisconsin. This study repre-

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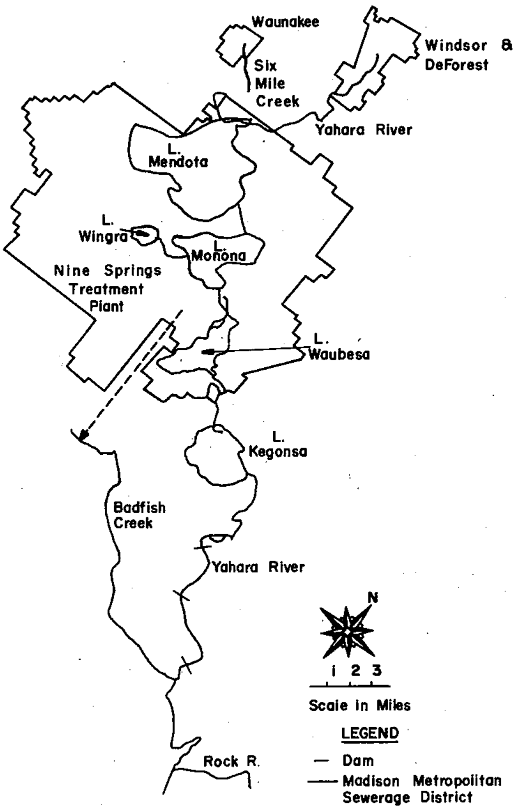

FIGURE 1.—Map of Madison lakes showing 1958 diversion and currently sewered area.

sents the only specific attempt to document scientifically the change in the chemical or biological status of a Madison lake after diversion. Lawton[1] has presented the results of this study through 1959. However, the study was continued through the summer of 1961, and a considerable amount of data was obtained; these data are currently unpublished.[6] In addition, recent data obtained by Fitzgerald *et al.*[7] make it possible to look at the current status of the lakes.

SOLUBLE PHOSPHORUS CHANGES

The mean winter concentration of soluble inorganic phosphorus (soluble ortho-P) in the Lake Waubesa outlet water is presented in Figure 2. These data, with the exception of the 1972–73 data, were originally compiled by Fruh and Lee[6] and later reported by Sonzogni and Lee.[3] The standard deviation, mean value, and number of observations are included in Figure 2 in order to give some idea of the precision of the data. Unfortunately, too few total phosphorus measurements were made to be of use in interpreting the effect of diversion on the total phosphorus content of the lake.

Although soluble ortho-P data are available for all seasons of the year, only the data collected during the winter are reported here. The winter values were thought to be the most reliable and comparable because of the fact that the data collected at other times of the year reflected the presence or absence of algal blooms in the water at the time of collection. In general, the standard deviation of the winter data was low compared with those of other seasons of the year. Because of the minimum biological activity during the winter, soluble phosphorus concentrations were at a level that was easily analyzed. Furthermore, it was expected that during the winter most of the total phosphorus would be in a soluble form.

Figure 2 shows a dramatic decrease in the soluble inorganic phosphorus of Lake

TABLE I.—Physical Characteristics of the Madison Lakes

Lake	Length (km)	Width (km)	Area (sq km)	Maximum Depth (m)	Mean Depth (m)	Volume (cu m $\times 10^{-7}$)	Hydraulic Residence Time (yr)
Mendota	9.5	7.4	39.4	25	12	48	4.5
Monona	6.6	3.9	14.0	22	8	12	1.1
Waubesa	6.8	2.3	8.3	10	5	4.2	0.2–0.3
Kegonsa	4.8	3.5	12.7	9	5	6.1	0.3–0.5
Wingra	2.1	0.8	1.3	4	—	0.6	—

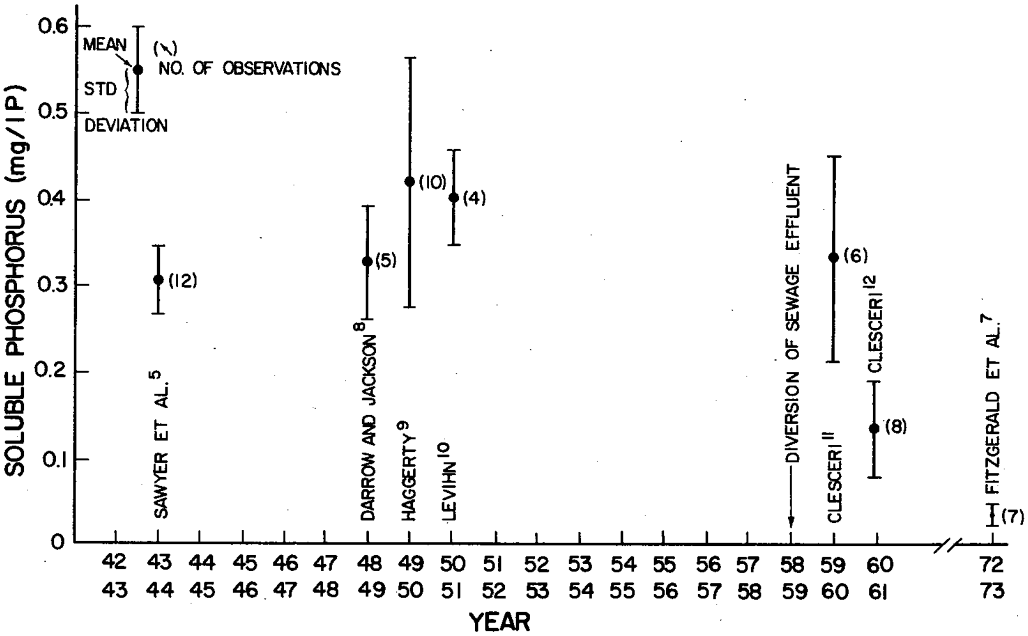

FIGURE 2.—Concentrations of soluble phosphorus in the outlet of Lake Waubesa during the winter.

Waubesa after diversion. Although no data are available, it is highly probable that the soluble ortho-P concentration in Lake Waubesa immediately before diversion was higher than that in 1950, which suggests that an even larger decrease actually occurred. Furthermore, the recent data in Figure 2 show that the soluble ortho-P concentration has remained at a low level compared with the pre-diversion data.

Lake Kegonsa, which is directly below Lake Waubesa in the chain of lakes (Figure 1), received most of its phosphorus loading from Lake Waubesa before the 1958 diversion.[5] Hence, the diversion of the wastewater effluent from Lake Waubesa also affected Lake Kegonsa. Figure 3 shows the response of Lake Kegonsa to the decreased phosphorus loading. The first winter after diversion, the soluble ortho-P concentration remained rather high, although the data displayed considerable variability, as judged from the high standard deviation. By the second winter after diversion, the Lake Kegonsa outlet water had a soluble ortho-P concentration similar to that of Lake Waubesa. Finally, nearly 15 yr after the diversion, even lower concentrations were found.

Based on the data available, the phosphorus contents of both Waubesa and Kegonsa seem to have responded rapidly and permanently to the decreased phosphorus loading. Of considerable importance is the fact that, following the diversion, the sediments of Waubesa and Kegonsa apparently did not act as major sources of phosphorus to the overlying waters during the winter. Consequently, the above examples present strong evidence against extensive buffering effects of the sediments, whereby phosphorus is released from the sediments in response to changes in the phosphorus concentration of the overlying water.[13] Modeling of the rate of recovery of these lakes has been discussed by Sonzogni and Lee[3] and Sonzogni *et al.*[14]

BIOLOGICAL CHANGES

A notable increase in the species diversity of the algae in the lower lakes was

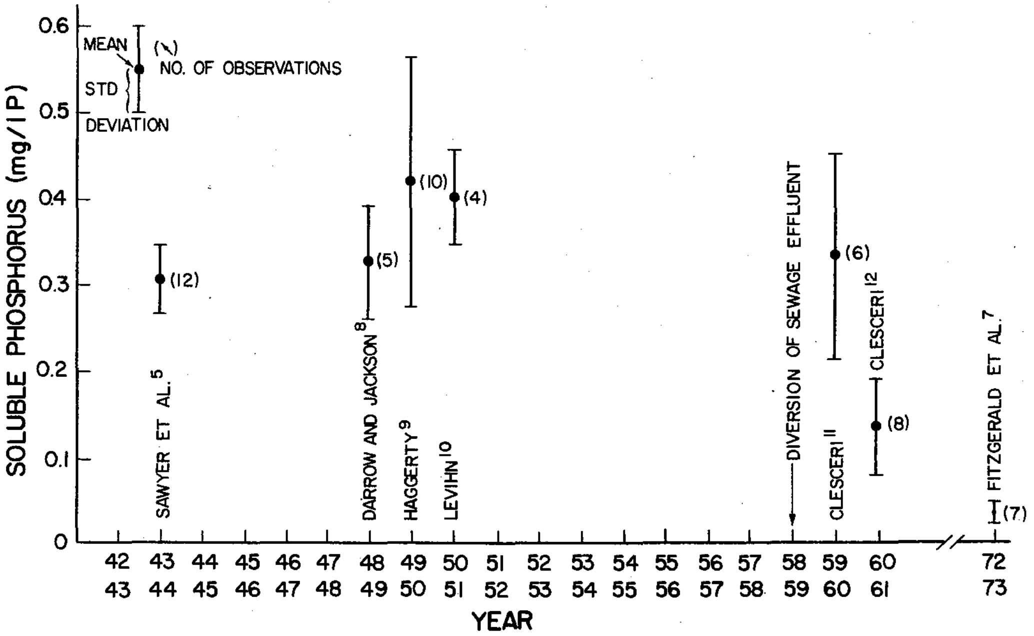

FIGURE 3.—Concentrations of soluble phosphorus in the outlet of Lake Kegonsa during the winter.

found after the diversion, particularly in Lake Waubesa. During the period before diversion (1955–1957), the algae of Lake Waubesa consisted of 99 percent *Microcystis*. Soon after diversion, there was a striking change in the number of algal species, as *Microcystis* decreased during the first summer following diversion to the point that it made up only 25 to 90 percent of the total number of algae. Recent evidence indicates that the algal population of Lake Waubesa has remained much more diverse than during the period when wastewater was entering the lake. Both Waubesa and Kegonsa may still be characterized as having frequent "pea soup" growths of algae during the summer months. However, because many of these algal blooms are caused by non-blue-green algae that generally do not form the highly obnoxious algal scum along the shore, it is generally felt that a significant improvement in water quality has occurred because of the diversion.

It is important to emphasize that the increased species diversity that occurred in the lower Madison lakes after diversion may not necessarily be caused by the reduced phosphorus content of these lakes. This diversion, in addition to reducing the phosphorus load to these lakes, also reduced the loads of many other chemical species. Based on the information available, it would be improper to attribute this change solely to the decreased phosphorus load.

PHOSPHORUS LOADING

Estimated phosphorus loadings for the lower Madison lakes are summarized in Table II. These estimates were based on calculations by Sonzogni and Lee[15] by using land use loading factors and atmospheric precipitation data obtained from local studies in the Madison area,[16] in addition to phosphorus and flow rate data from the Yahara River at the lake outlets. It should be emphasized that these estimates of loading rates are predicated on many assumptions and are, at best, only rough approximations. Nutrient loadings could vary widely from year to year, depending

TABLE II.—Phosphorus Loading to the Lower Madison Lakes

	Lake Waubesa				Lake Kegonsa			
	Soluble Ortho-P		Total P		Soluble Ortho-P		Total P	
	kg/yr	Total (%)	kg/yr	Total (%)	kg/yr	Total (%)	kg/yr	(%)
Wastewater discharge	0	0	0	0	900	6	1,000	4
Urban runoff	2,000	15	3,000	14	300	2	400	2
Rural runoff	2,000	15	5,000	23	4,000	26	7,000	30
Precipitation on lake surface	100	1	200	1	200	1	300	1
Dry fallout on lake surface	100	1	700	3	200	1	1,000	4
Yahara River	9,000	68	13,000	59	10,000	64	14,000	59
Woodland runoff	0	0	0	0	0	0	0	0
Marsh drainage	0	0	0	0	0	0	0	0
Total	13,200	—	21,900	—	15,600	—	23,700	—

on climatic conditions and other factors. Nonetheless, the estimates are believed to be the most current and reasonable estimates, based on the data available.

In Table II, it may be seen that the largest source of phosphorus to Waubesa and Kegonsa is the Yahara River. The Yahara River is also the largest phosphorus source for Lake Monona, the second lake in the chain (Figure 1). The total annual phosphorus loading for Monona is estimated to be 13,200 kg of soluble ortho-P and 21,900 kg of total P. In contrast, Lake Mendota, the headwater lake, which has a much larger drainage basin than do the lower lakes, receives most of its input from rural runoff. Mendota also has the highest phosphorus loading, with about 36,300 kg of soluble ortho-P and 63,100 kg of total P estimated to enter the lake each year. Rural runoff is the second most important source for Lake Waubesa and Lake Kegonsa, as shown in Table II.

The new nutrient loading estimates for the lower lakes are much lower than the pre-diversion estimate of Sawyer *et al.*,[5] who found the loading (including wastewater input) of soluble ortho-P to be 58,700 kg and 53,900 kg for Waubesa and Kegonsa, respectively. Nonetheless, despite this large reduction in the phosphorus loading, Waubesa and Kegonsa are still highly eutrophic, as was discussed previously. However, when the phosphorus loading to each of the Madison lakes is considered on a unit surface area or volume basis (Table III), Lake Waubesa is found to have the highest unit loading rates, followed by Kegonsa, Monona, and Mendota. The eutrophic status of these lakes, as measured by the severity and frequency of obnoxious algal blooms and nuisance macrophyte growth, is generally in accordance with this order. The unit loading rates are particularly high for Waubesa and Kegonsa compared with Mendota and Monona. Thus, it is not surprising that, despite the 1958 wastewater diversion, Waubesa and Kegonsa still have frequent "pea soup" growths of algae and nuisance growths of aquatic weeds and that their water quality is considered to be significantly poorer than that of the deeper lakes, Mendota and Monona.

TABLE III.—Phosphorus Loading to the Lower Madison Lakes per Unit Surface Area of Volume

Lake	Area and Lake Volume			
	kg/ha/yr		kg/cu m/yr	
	Soluble Ortho-P	Total P	Soluble Ortho-P	Total P
Mendota	9	16	0.08	0.13
Monona	11	18	0.13	0.21
Waubesa	16	26	0.33	0.51
Kegonsa	12	19	0.25	0.40

It is important to realize that a given unit volume phosphorus loading is likely to result in a greater overall productivity in shallow lakes, such as Waubesa and Kegonsa, compared with relatively deep lakes, such as Mendota and Monona, which permanently stratify during the summer. In thermally stratified lakes, a significant portion of the phosphorus mineralized from raining or settled algae is trapped below the thermocline during most of the summer growing season. However, in shallow, generally well-mixed lakes, mineralized phosphorus is readily transported to the photic zone, where it may potentially stimulate additional algal growth. In other words, shallow lakes are usually capable of recycling nutrients to the photic zone during the growing season to a greater extent than are stratified lakes. Thus, in addition to the current high loading rates, the shallow nature of the lower Madison lakes must be considered when evaluating the highly eutrophic conditions that exist despite the 1958 diversion.

It should be mentioned that the current soluble ortho-P annual cycle, as measured at the lake outlets, is quite different for Waubesa as compared with that of Kegonsa. Waubesa has high phosphorus concentrations during the winter and low concentrations during the summer, similar to the pattern in Mendota and Monona. This reflects to a large extent the Yahara River loading, which is generally greatest during the winter and lowest during the summer, as well as the action of aquatic weeds and algae in removing soluble ortho-P in the summer. Measurements of *in situ* algae from Waubesa also indicate that the phosphorus content of the algae correlates with the phosphorus content of the water at the time the algae were sampled.

Data from the Kegonsa outflow, however, indicate that a different pattern exists for Lake Kegonsa. During the late spring and early summer of both 1972 and 1973, the soluble ortho-P concentrations in the outlet water decreased to low values (0.02 to 0.03 mg/l P), much like those of the other lakes. However, there was a striking increase in soluble ortho-P in the Kegonsa outlet, to about 0.10 mg/l P, during August and September. This occurred in 1971, 1972, and 1973. The extractable ortho-P content of the algae also increased during this period. An increase in the soluble ortho-P concentration also occurred in the Waubesa outlet water during the late summer of 1972 and 1973, but not to the same extent as was observed for Kegonsa. It should be emphasized that, despite these summer increases, soluble ortho-P concentrations were still much lower than prediversion concentrations.

It was originally thought that the higher levels of soluble ortho-P in Kegonsa compared with those of Waubesa during the late summer might be attributed to septic tank drainage from the summer cottages along the shore of Lake Kegonsa. However, based on the estimated nutrient input from septic tanks (Table II), it does not seem that septic tank seepage could account for the large increase observed. Nevertheless, because sewers are scheduled to replace the septic tanks in the near future (the wastewater will ultimately be diverted around the lake), it should be possible to demonstrate conclusively whether the septic tanks were a significant phosphorus source.

Hutchinson[17] cited several examples of lakes, both in the U.S. and Europe, in which a striking increase in the soluble phosphorus concentration of the surface water was observed during the summer. This increase was thought to be caused, at least in part, by the decomposition of large blooms of algae. However, no data are available to indicate that plant decomposition is responsible for the large phosphorus increase in Lake Kegonsa, but it is a possibility. Weeds are cut from certain areas of the lake but are removed immediately after cutting. Although copper sulfate was once used to control algae, it has not been used in the last few years.

Probably the most likely explanation for the late summer increase in phosphorus would be the transfer of phosphorus from the sediments to the overlying water. Because of the high productivity of Waubesa and Kegonsa, anaerobic conditions, which tend to promote phosphorus solubilization, probably develop at the lake bottoms during periods of temporary stratification. The larger increase in the phosphorus content in Kegonsa compared with that in Waubesa could be a result of the fact that Kegonsa has a larger sediment surface area than does Waubesa. (The surface area of Kegonsa is about 1.5 times larger than that of Waubesa, although the lakes have about the same mean depth; see Table I). Thus, on a unit area basis, there is a greater capacity for phosphorus release from the sediments in Kegonsa versus those in Waubesa. The possible transfer of phosphorus from anaerobic mud layers during the late summer may be promoted by wind induced stirring or by mixing by bottom-feeding fish (the lakes support a large population of carp and bullheads) and benthic organisms. Future research should be directed toward evaluating the mechanisms of sediment-water interchange of phosphorus in these lakes.

IN-LAKE CONCENTRATION VERSUS LOADING

It is possible to predict the average annual concentration of phosphorus within a lake, based on the annual input of phosphorus. As a first approximation from the standpoint of long-term trends, a lake such as Waubesa or Kegonsa may be assumed to approximate a completely mixed reactor subjected to continual and constant chemical influx. As discussed by Sonzogni *et al.*,[14] if it is also assumed that the main loss of phosphorus to Waubesa and Kegonsa is to the outlet, which is reasonable for these lakes because of their short hydraulic residence times,[3] the average annual steady-state concentration should be equal to the product of hydraulic residence time and the annual input. From this relationship, it is possible to predict the in-lake concentration and compare it with actual data.

The average annual flow of the Yahara River at the outlet of Lake Waubesa in the early 1940's was on the order of 3.8×10^5 cu m/day. If this flow is divided into the volume of Lake Waubesa (Table I), a theoretical hydraulic residence time of about 0.3 yr is obtained. By using this residence time and an annual tributary input of soluble inorganic phosphorus of 5.9×10^4 kg P, as determined by Sawyer *et al.*,[5] the steady-state concentration is estimated to be about 0.43 mg/l P. This is remarkably close to the average annual concentration of 0.42 mg/l P measured by Sawyer *et al.*

Currently, the hydraulic residence time of Lake Waubesa is estimated to be on the order of 0.25 yr. By using this residence time and a current annual soluble ortho-P loading of 13,200 kg, the steady-state concentration is estimated to be about 0.075 mg/l P. This concentration is again quite close to the measured average annual concentration of 0.05 mg/l P. Similar calculations showing good agreement between actual and predicted concentrations may be made for Kegonsa. These calculations indicate that the estimated nutrient loadings are reasonable and that the lakes have responded to the diversion in a predictable manner.

CONCLUSION

Based on the data available, there has been a positive and rapid response to the diversion of wastewater from the lower Madison lakes. This response is easily seen through a decrease in the soluble ortho-P concentration as well as an increase in the species diversity of algae in the lakes immediately after diversion. Current data, obtained nearly 15 yr since the diversion was initiated, indicate that species diversity has remained significantly higher than it was before diversion and that the phosphorus concentration has remained comparatively low. To be sure, the lakes are still highly eutrophic, at least relative to the larger Madison lakes, Mendota and Monona, but this is understandable when their phosphorus income on a unit volume or unit surface area basis and their shallow depth are considered.

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