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DIVERSION OF WASTEWATERS FROM MADISON LAKES[a]

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INTRODUCTION

One of the most effective means of controlling or minimizing lake eutrophication is by reducing the rate of nutrient flux into lakes. Although diffuse sources of nutrients, such as agricultural runoff or urban drainage, are sometimes difficult to control, the influx from sewage effluent or other point sources generally may be readily eliminated or reduced. From a long-range point of view, the best way to accomplish this is by the tertiary treatment of the point source, but perhaps the most frequently used method is the diversion of point sources of nutrients, such as municipal waste waters, around the lake of concern. While the diversion method does eliminate the source of nutrients from the original lake that received nutrients, the problem may be transferred to the receiving water. Nevertheless, this approach has been used in Madison, Wisc., as well as in a few other cities, the most notable example being Seattle, Wash. [see Edmondson (9)]. In general, relatively little information has been published on the change in water quality, particularly quantitative changes in the nutrient content of the lakes, as a result of manipulating waste water disposal sites.

The purpose of this paper is to examine the effect of waste water diversion on the water quality of the Madison lakes and on the water quality of the receiving waters of the diverted effluent, with particular attention devoted to the change in the phosphorus content of the lakes and receiving waters following

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diversion. The use of elementary mathematical relationships to determine the expected rate of recovery of excessively fertilized lakes after a reduction in the phosphorus input will be considered and a prediction of the effect of a recent wastewater effluent diversion at the headwater of the Madison lakes will be presented.

Characteristics of Madison Lakes

The five Madison lakes, among the most studied lakes in the world, are hard-water, eutrophic lakes formed by morainic damming during the most recent ice age. The lakes drain a watershed composed mostly of fertile, highly cultivated farmland, and urban area. Four of the lakes, Lake Mendota, Lake Monona, Lake Waubesa, and Lake Kegonsa, form a chain of lakes along the Yahara River as shown in Fig. 1. The current sewered area of metropolitan Madison and the scheme of flow of treated wastewater is also shown in Fig. 1. Lake Mendota is the largest and deepest of the lakes, followed in order of area and depth by Monona, Kegonsa, and Waubesa. Lake Wingra, the smallest and shallowest of the five Madison lakes, is spring fed and drains into Lake Monona (Fig. 1). Pertinent physical characteristics of the lakes are summarized in Table 1. A synopsis of limnological information on the lakes may be found in Frey (11).

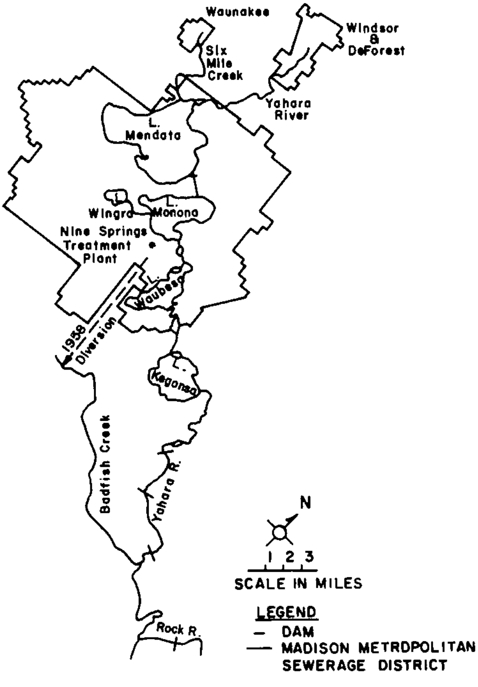

FIG. 1.—Map of Madison Lakes Showing 1958 Diversion and Current Sewered Areas

TABLE 1.—Physical Characteristics of Madison Lakes[a]

Lake (1)	Length, in kilometers (2)	Width, in kilometers (3)	Area, in square kilometers (4)	Maximum depth, in meters (5)	Mean depth, in meters (6)	Volume, in cubic meters $\times 10^{-7}$ (7)	Hydraulic residence time, in years (8)
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	—

[a] After Lawton (14).

TABLE 2.—History of Waste Treatment and Disposal in Madison, Wisc.[a]

Date (1)	Development (2)
1820-1898	Early cultural period—privies, cesspools, and direct drains emptying into Lake Mendota and Lake Monona.
1895	Sewerage system started.
1898	First treatment plant utilizing chemical treatment and sand filtration, built on Yahara River between Lakes Mendota and Monona. Filters drained into Yahara River near inlet to Lake Monona.
1902	Turneaure plant, employing septic tanks and filtration through cinder filters, replaced original plant. Effluent discharged to Lake Monona.
1914	Burke treatment plant replaced Turneaure plant. Primary settling tanks and trickling filters used. Effluent discharged to Lake Monona.
1928	First unit of Nine Springs plant constructed. Imhoff tanks followed by trickling filters and final clarifiers used. Effluent discharged to Lake Waubesa.
	Burke plant still operating in accordance with its rated capacity and discharging to Lake Monona.
1936	Nine Springs plant enlarged by the addition of an activated sludge system.
1937	Burke plant closed—all of Madison's sewage treated at Nine Springs and the effluent disposed to Lake Waubesa.
1942-1946	Burke plant returned to operation to service a military camp. Effluent disposed to Lake Monona.
1947-1950	Burke plant reactivated during installation of east side interceptor. Effluent disposed to Lake Monona.
1950	Burke plant closed. All wastes again treated by Nine Springs plant. Effluent disposed to Lake Waubesa.
1958	Effluent from Nine Springs plant diverted around all the Madison Lakes.
1971	Waste water from DeForest and Waunakee diverted from Lake Mendota tributaries to Nine Springs Plant.

[a] After Lawton (14).

EFFECT OF WASTEWATER DIVERSIONS IN MADISON

The diversion of sewage effluent around a lake as a means of retarding lake degradation is not a new practice in Madison. Before the turn of the century the first major diversion of sewage was accomplished when the domestic wastewaters from the rapidly growing City of Madison were diverted around Lake Mendota. Since that time there have been several wastewater diversions and sewage treatment innovations. Their development is outlined in Table 2. The often chaotic political circumstances which led to the decisions regulating wastewater disposal in Madison's early history have been reviewed by Flannery (10) and Sarles (23).

Mendota Diversion (1898).—The first major diversion in Madison occurred in the late nineteenth century when a sewerage system was developed to service the City of Madison, the city at that time being confined to the isthmus between Lake Mendota and Lake Monona. Sewage from the city was no longer allowed to flow directly into the lakes, but the early treatment plant discharged its effluent into the Yahara River near the entrance to Lake Monona. Of course, at that time it was not known that sewage was a major source of plant nutrients that stimulate biological production. The early diversion was implemented primarily for public health and esthetic reasons. No report is available as to whether there was a noticeable improvement in Lake Mendota after the diversion. It is very likely that other nutrient inputs associated with the urbanization of Madison, which was rapidly occurring at that time, may have overshadowed any beneficial effect of the nutrient reduction.

Monona Diversion (1936, 1950).—The original plant which treated Madison's sewage was replaced by the Turneaure Treatment Plant in 1902 (Table 2). Discharge from the Turneaure Plant still entered Lake Monona, but the new plant rendered better treatment, as evidenced by a decrease in objectionable odors and plant growth according to boatmen and residents of Lake Monona (23). In 1914, the Burke Treatment Plant replaced the Turneaure Plant and a further improvement in sewage treatment was obtained. Nevertheless, because the City of Madison was rapidly increasing in population, the Burke Plant soon became overloaded and the volume of wastewaters entering Lake Monona intensified. Nuisance growths of algae and obnoxious odors from the lake increased in frequency. In order to control this condition, treatment of the lake with copper sulfate was implemented.

In 1928, after considerable public debate, Madison completed construction of the Nine Springs Sewage Treatment Plant (Table 2). The effluent from this plant was discharged into Nine Springs Creek, which flowed into the Yahara River above Lake Waubesa. Despite this new plant, the Burke Treatment Plant remained in operation and wastewater continued to be discharged into Lake Monona until 1936, when all of Madison's sewage was treated at the Nine Springs Plant. After 1936, no sewage effluent was discharged directly into Lake Monona until 1942, when it was necessary to reactivate the Burke Treatment Plant to accomodate a military installation put into operation during World War II. Finally, in 1950 domestic sewage was completely diverted around Lake Monona (Table 2).

During periods when Lake Monona was not receiving effluent, there was a slow improvement in the condition of the lake as evidenced by the lesser quantity of copper sulfate required to control the algae (8). Since 1962 Lake Monona has not received chemical treatment for algae control. The lake still has a large population of algae, but scum-forming species have not been as prevalent as in previous years.

Caution should be exercised in attempting to interpret water quality in a lake based on the amounts of chemicals such as copper sulfate used for algae control. For many years there has been a strong anti-chemical control group in Madison. In recent years this group has gained sufficient political power to have the Madison City Council adopt an ordinance prohibiting the use of chemicals for aquatic weed and algae control. The decreased use of copper sulfate in Lake Monona in the last 20 yr reflects, to some extent, the increasing effectiveness of the anti-chemical control forces in the local politics of Madison.

No chemical studies were specifically made to determine the consequence of the 1950 sewage diversion around Lake Monona. However, some phosphorus analyses were made on samples taken from the Lake Monona outlet, both before and after 1950, in conjunction with various limnological studies of the Madison lakes. These data, although very limited, can give some insight on the response of Lake Monona to the decreased phosphorus input following diversion.

The mean winter concentration of soluble inorganic phosphorus (soluble orthophosphate) in the Lake Monona outlet water, as measured by various investigators since 1940, is presented in Fig. 2. These data were originally compiled in 1965 by Fruh and Lee in an unpublished manuscript of the University of Wisconsin Water Chemistry Program entitled "The Eutrophication of the Madison Lakes." The standard deviation, mean value, and number of observations are included in Fig. 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 phosphorus content of the lake.

Although soluble inorganic phosphorus data are available for all seasons of the year, only the data collected during the winter are reported herein. The winter values were thought to be the most reliable and comparable as a result of the fact that the data collected at other times of the year reflect 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 to other seasons of the year. Because of minimal biological activity during the winter, soluble phosphorus concentrations were at a level which was easily analyzed. Furthermore, it would be expected that during the winter most of the total phosphorus was in a soluble form.

Fig. 2 shows that the soluble inorganic phosphorus concentration increased from about 0.06 mg/l P during the winters of 1942-1943 and 1943-1944, when sewage was again entering Lake Monona from the Burke Sewage Treatment Plant, to about 0.1 mg/l P at the end of the decade. In the winter of 1950-1951, after sewage had finally been diverted around Lake Monona, the concentration of soluble inorganic phosphorus deceased to about an average of 0.04 mg/l P. Approx 10 yr later even lower values were found. Thus, the available data indicate a decrease in the soluble inorganic phosphorus concentration in the Lake Monona outlet water following diversion. Unfortunately, the rate at which the lake responded to the reduced phosphorus input cannot be deciphered from the limited data on hand.

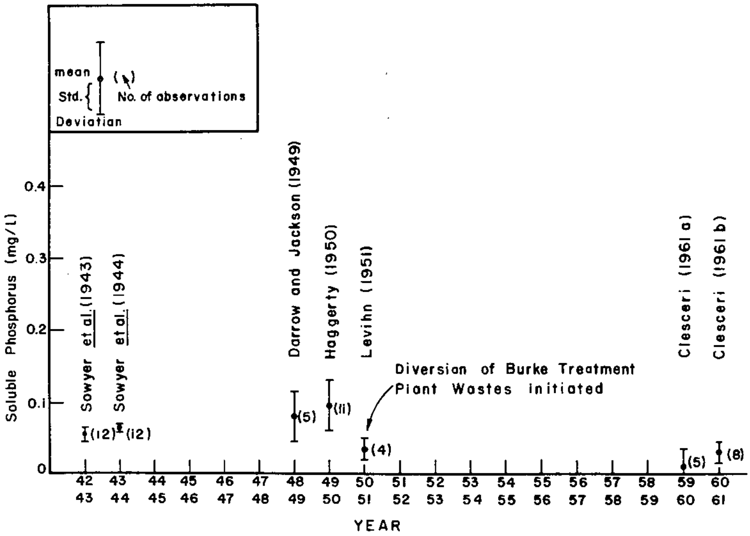

FIG. 2.—Concentrations of Soluble Phosphorus in Outlet of Lake Monona During Winter (After Fruh and Lee, 1965)

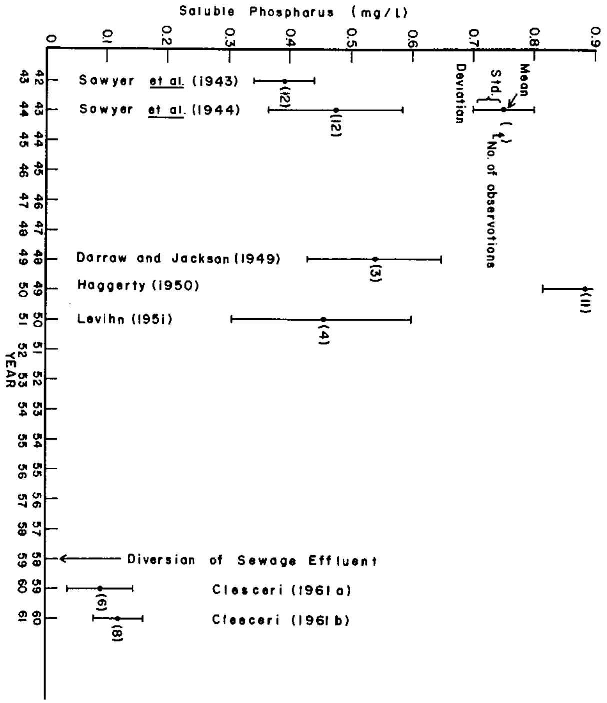

FIG. 3.—Concentration of Soluble Phosphorus in Outlet of Lake Waubesa During Winter (After Fruh and Lee, 1965)

Waubesa Diversion (1958).—In 1938 the Nine Springs Treatment Plant began discharging its effluent into the Yahara River above Lake Waubesa (Fig. 1) and the lake immediately began to show the increased effects of nutrient enrichment. Chemical treatment was practiced to control the severe nuisance of algal blooms and aquatic weeds which developed.

As a consequence of the public's displeasure over the condition of Lake Waubesa and the denial by some individuals that sewage was a factor in stimulating algal growth, a detailed study of the sources of nutrients was spurred. The study, under the direction of Sawyer (24,25), was unique in that a detailed nutrient budget was determined for the first time by measuring the amounts of nutrients entering a lake from various sources. Sawyer et al. (24,25) found that 88% of the inorganic phosphorus loading received by the lake each year was derived from the Nine Springs Sewage Treatment Plant effluent. Thus, the study clearly demonstrated that sewage was a major source of aquatic plant nutrients (i.e., phosphorus) for Lake Waubesa.

Finally, after much public debate and community bickering, it was decided that Madison's treated sewage effluent should be completely diverted around Madison's lakes. In December, 1958 this diversion was completed and effluent from the Nine Springs Plant is now discharged to the lower Yahara River around all the Madison lakes via Badfish Creek (see Fig. 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 represents the only specific attempt in the past to scientifically document the change in the chemical or biological status of a Madison lake after diversion. Lawton (14) 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 were obtained which are currently unpublished (the data have been complied in an unpublished manuscript by Fruh and Lee, 1965).

A notable increase in the species diversity of the algae in Lake Waubesa was found after diversion which is an indication of improved water quality. According to Lawton's (14) report, the algae of Lake Waubesa consisted of 99% *Microcystis* during the period prior to diversion (1955-1957). After diversion, there was a striking change in the number of algal species, as *Microcystis* decreased to the point where it made up only 25%-90% of the total number of algae. Rai, et al. (unpublished data, Water Chemistry Program, University of Wisconsin, 1965), using preserved samples collected from the Lake Waubesa outlet after diversion by Clesceri (6), also found a more diverse composition of algae than was reported before diversion. Recent evidence indicates that the algae population in Lake Waubesa is still more diverse than prior to the nutrient diversion.

Soluble inorganic phosphorus data for the Lake Waubesa outlet, obtained during the winter period both before and after diversion, are shown in Fig. 3. As explained in the analysis of the Lake Monona data, only the winter values have been presented. Fig. 3 shows a dramatic decrease in the soluble inorganic phosphorus after diversion. Although no data are available, it is highly probable that the soluble inorganic phosphorus concentration in Lake Waubesa immediately before diversion was higher than in 1950, which suggests that an even larger decrease actually occurred.

Lake Kegonsa, which is directly below Lake Waubesa in the chain of lakes

(Fig. 1), received most of its phosphorus loading from Lake Waubesa prior to the 1958 diversion (25). Thus, the diversion of the sewage effluent from Lake Waubesa also affected Lake Kegonsa. Fig. 4 shows the response of Lake Kegonsa to the decreased phosphorus loading. The first winter after diversion the soluble inorganic phosphorus 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 inorganic phosphorus concentration similar to Lake Waubesa.

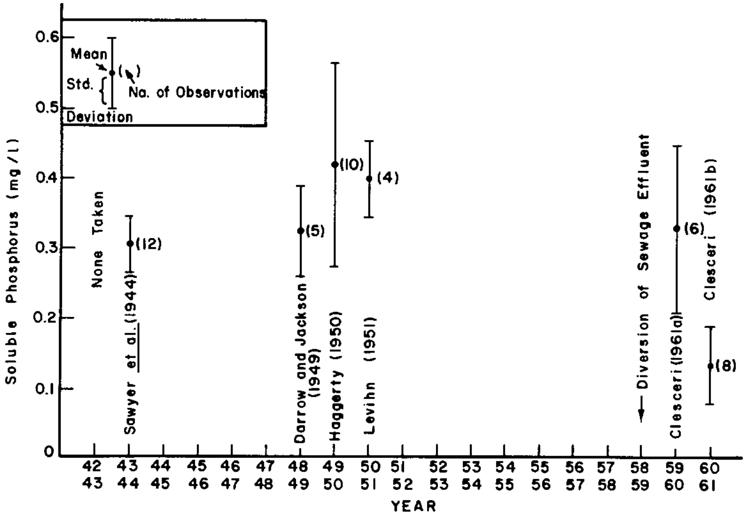

FIG. 4.—Concentrations of Soluble Phosphorus in Outlet of Lake Kegonsa During Winter (After Fruh and Lee, 1965)

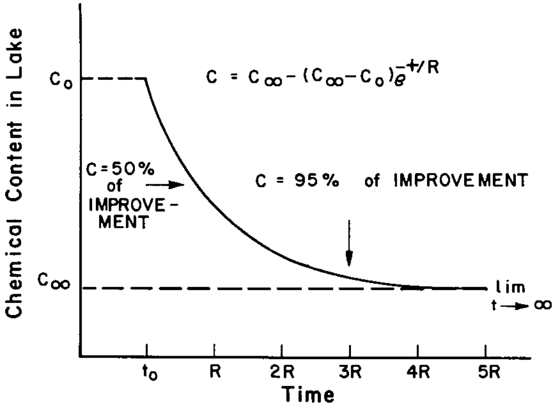

FIG. 5.—Role of Recovery of Lake Following Reduction at Influx of Conservative Chemical

It is regrettable that studies of the effects of the 1958 diversion were terminated after only 2 yr. A much more comprehensive study, covering several years before and after diversion, was needed in order to conclusively ascertain the lakes' recovery. Nevertheless, based on the limited data available, there appears to have been a definite decrease in the soluble inorganic phosphorus content in Lake Waubesa, and to a lesser extent, Lake Kegonsa, within 1 yr-2 yr after diversion.

From the limited data available, note that the diversion resulted in improved water quality in the lower Madison lakes, primarily as a result of a decrease in the frequency and severity of blue-green algal blooms in these lakes. These lakes, after diversion, could still be characterized as having frequent "pea soup" growths of algae during the summer months. However, since many of these algal blooms were due to nonblue-green algae which generally do not form the highly obnoxious algal scum along the shore, the residents of the lower Madison lakes generally felt that the decreased frequency of the obnoxious scum represented a significant improvement in water quality.

Effect of 1958 Diversion on Receiving Waters.—The diversion of the Madison wastewater effluent to Badfish Creek, which empties into the Yahara and Rock Rivers below the Madison lakes, has generally improved the water quality of the two lower Madison lakes. Nevertheless, the problems associated with the wastewater have been transferred to some extent to the receiving waters, as there has been an impairment of the water quality of the Badfish Creek and to some extent the stretch of the Yahara River below the confluence of the creek and the Rock River (1,16,17,19,29). At the point where the Nine Springs Sewage Plant effluent enters Badfish Creek approx 75% of the total creek flow, currently about 40 mgd, is treated effluent. Even though the Madison Nine Springs Sewage Treatment Plant is doing an excellent job in accord with expected performance of an activated sludge-type plant, it is reasonable to expect that with such a large percentage of flow in the creek derived from the treated wastewater effluent, some water quality problems would be found.

Recently, Lee and Veith (16) reviewed 19 yr of data made available by the Madison Metropolitan Sewerage District, which included the results of analysis of samples taken at stations on the Badfish Creek, Yahara, and Rock Rivers. Samples were analyzed for soluble and total phosphate as well as many other parameters. In general, it was deduced from the data that the Madison Nine Springs Sewage Treatment Plant effluent currently contributes large amounts of phosphorus to the Badfish Creek, Yahara, and Rock Rivers, although significant amounts of phosphorus are contributed by other sources. It has been estimated that approx 50% of the phosphorus present in the Rock River below the confluence of the Yahara and Rock Rivers is derived from the Madison Nine Springs Plant (17). It should be pointed out that prior to the 1958 diversion, the Rock River still received nutrients from the Nine Springs plant, but the effluent then passed through both Lake Waubesa and Lake Kegonsa as well as several small natural or artificial impoundments along the Yahara River between Lake Waubesa and the confluence of Badfish Creek and the Yahara River. When the effluent passed through these lakes and impoundments, some of the phosphorus was likely to have been removed. This is because most lakes and other slow moving water bodies tend to act on an annual cycle as nutrient traps by accumulating phosphorus in lake sediments as a result of chemical and biological precipitation. A comparison of recent data on the concentrations of soluble phosphorus in the Yahara River below the point where Badfish Creek joins it with data prior to diversion shows that the amounts of phosphorus found in the river at this point have increased (16). However, the higher levels found today are attributable in part to increases in the phosphorus content of the Madison effluent. The amount of soluble inorganic phosphorus present in the Madison effluent has almost doubled since before diversion (16). Thus, even if the diversion did not take place, it is likely that the fertility of the Yahara and Rock Rivers would have increased since 1958.

The nutrient-rich Madison wastewater effluent is currently stimulating excessive growths of weeds and algae, particularly attached algae, in receiving waters. This is especially true in Badfish Creek and the diversionary ditch leading to the creek. In fact, aquatic plant growth is at times so luxuriant that water transport is impeded, thereby necessitating mechanical aquatic plant harvesting in Badfish Creek. Excessive algae and macrophytes in the Badfish Creek and parts of the Yahara River probably also result in dissolved oxygen deficiencies in the waters during early morning hours as a result of the respiration of these plants. Moreover, a high and relatively constant oxygen demand is exerted by the microbial utilization of the organic matter derived from the waste water effluent, the typical 5-day BOD of the treated effluent ranging from 18 mg/l-22 mg/l. Nitrification of the 10-mg/l ammonia nitrogen present in the wastewater also exerts a high oxygen demand. Although no actual data are available on the diurnal dissolved oxygen concentrations in these waters, based on studies conducted by students from the Department of Civil and Environmental Engineering at the University of Wisconsin (2) and the experience of the writers with similar streams, it appears that dissolved oxygen concentrations will likely diminish to the extent that they prohibit the existence of certain types of fish and aquatic life in lower Badfish Creek and in parts of the Yahara River.

Mendota Diversion (1971).—The most recent sewage diversion affecting the Madison area occurred in December, 1971, when the wastewaters from Waunakee and DeForest, two small municipalities north and west of Madison (Fig. 1), were diverted from entering Lake Mendota. Wastewater from the town of Windsor, the only major source of municipally treated wastes remaining for Lake Mendota, is scheduled to be diverted in the near future. The diversion is estimated to reduce the annual phosphorus loading to Lake Mendota by approx 20% (26).

As part of a University of Wisconsin Water Chemistry project aimed at modeling the aqueous environmental chemistry of nitrogen and phosphorus in Lake Mendota, the amounts and forms of nitrogen and phosphorus, as well as several other parameters, are being determined at meter intervals of depth in the lake each week. This monitoring program was initiated in the summer of 1970 and is planned to continue for some time; it will be possible to observe the changes, if any, resulting from this diversion. At this point in time it is too early to expect to see any effect of this diversion on water quality in Lake Mendota for reasons presented in the following.

MODELING POTENTIAL RESPONSE TO DIMINISHED PHOSPHORUS INPUT

A simple, exponential decay model, based on a lake's hydraulic residence time or water residence time (volume of the lake divided by the inflow or throughput), can be used to predict the time required for a conservative chemical (one that does not enter into biological or chemical reactions in the lake) to reach a new steady-state content following a reduction of the chemical input. A graphical and mathematical representation of this model is presented in Fig. 5. The model follows from a mass balance on a conservative chemical around a lake which, from the standpoint of long-term trends, is assumed to approximate a completely mixed reactor subjected to a constant chemical input. According to this approach, the content of a chemical in a lake (C) is determined by the chemical influx and the hydraulic residence time (R) and should decrease exponentially following a reduction in the influx. After a period of time equal to about three hydraulic residence times, the concentration in the lake should be equal to 95% of the difference between the initial lake concentration (C_0) and the new steady state concentration (C_∞).

Rate of Recovery of Lake Kegonsa and Lake Waubesa Following 1958 Diversion.—Although the model based on the hydraulic residence time has been used to theoretically predict the response of lakes to pollution abatement (7,22), few, if any, attempts have been made to apply the model to an actual situation. Therefore, it is of interest to compare, using the limited data available, the observed rate at which the phosphorus content of Lake Waubesa and Lake Kegonsa responded to the 1958 diversion with that predicted by the model, assuming that phosphorus behaves as a conservative chemical.

The average annual flow of the Yahara River in the early 1960's as measured by Sawyer et al. (24,25), was on the order of 100 mgd (4.4 m^3/s) which was about the average annual flow between 1939 and 1958 as measured at a USGS gaging station located at the outlet of Lake Waubesa (12). If this flow is divided into the volume of the lake (Table 1), a theoretical hydraulic or water residence time of about 0.3 yr is obtained. Using this residence time and an annual tributary input of soluble inorganic phosphorus of 1.3×10^5 lb P (4.8×10^7 g P) as determined by Sawyer, et al. (24,25), the steady-state content is estimated to be about 1.8×10^7 g P or about 0.43 mg/l P. This is remarkably close to the winter concentrations actually measured by Sawyer, et al. (24,25) as shown in Fig. 3.

Again using a flow rate of 100 mgd (4.4 m^3/s) and the data in Table 1, the hydraulic or water residence time for Lake Kegonsa for the early 1940's is calculated to be about 0.44 yr. According to Sawyer, et al. (24,25) Lake Kegonsa received an average soluble phosphorus loading of about 1.2×10^5 lb P/yr (4.5 g P/yr), almost all of which came from the outflow of Lake Waubesa. Based on this information, the average steady-state concentration is calculated to be about 0.38 mg/l P. This predicted concentration is also surprisingly close to the average winter concentrations of Lake Kegonsa measured by Sawyer, et al. (24,25) as shown in Fig. 4.

The average Yahara River flow for the water year 1960 and 1961 was 140 mgd (6.2 m^3/s), somewhat higher than the prediversion average flow despite the fact that the flow was reduced by about 22 mgd (1.0 m^3/s as a result of the Badfish Creek diversion (12). Thus, the theoretical hydraulic residence time may be estimated to be about 0.22 yr immediately after diversion. If sewage effluent is taken to have contributed 90% of the input of soluble inorganic phosphorus (25), then, according to Fig. 5, in less than 1 yr after the December, 1958, sewage diversion, the equilibrium concentration of phosphorus should have been reduced by nearly 90%. Unfortunately, there is no information on what the soluble inorganic phosphorus concentration was the winter immediately prior to diversion. However, compared to 1950 and earlier, the mean winter outlet concentration one year after diversion was reduced by over 75% (Fig. 3). Assuming that the outlet concentration is equal to the mean concentration in the lake, the soluble inorganic phosphorus content of the lake was reduced by over 75%.

Using a Yahara River flow of 140 mgd (6.2 m^3/s), a post-diversion hydraulic or water residence time of about 0.31 yr is calculated for Lake Kegonsa. Since Lake Kegonsa was thought to receive most of its soluble inorganic phosphorus input from Lake Waubesa (24,25), a 90% reduction in the phosphorus entering Lake Waubesa should also have resulted in nearly a 90% reduction in the input to Lake Kegonsa. However, the rate of recovery of Lake Kegonsa depended not only on its own flushing period but also on that of Lake Waubesa and the reach of the Yahara River between the two lakes (including a small shallow lake-like widening of the river, as shown in Fig. 1). Thus, the combined theoretical hydraulic residence time should have been slightly greater than 0.53 yr, so that Lake Kegonsa should have reached 95% of its new equilibrium phosphorus concentration within approx 2 yr. This represents a rough upper bound to the rate of recovery, since by combining residence times it is assumed that Lake Kegonsa did not begin to recover until Lake Waubesa was at steady state with the reduced input (approx 1 yr after the diversion).

The first winter after diversion, the observed data reveal a small decrease in the soluble inorganic phosphorus concentration in the outlet of Lake Kegonsa compared to 1950 values, while the second winter after diversion the soluble inorganic phosphorus concentration was reduced by nearly 70%. Again, the lack of data immediately prior to diversion precludes a more accurate assessment of the situation, but it appears that the observed rate at which Lake Kegonsa equilibrated to the decreased chemical flux, assuming the concentration in the outlet water was equal to the concentration in the lake, was close to the rate predicted by the simple model based on the hydraulic residence time.

Note that the apparent rate of recovery of the lower Madison lakes was approximately equal to the rate predicted by the hydraulic residence time model. This observation points to the fact that the sediments of these lakes did not act as a major source of phosphorus to the overlying waters following diversion. In other words, the often alluded to phosphate buffering of lake sediments did not occur to any significant extent in these lakes. As analyzed by Lee (15) shallow lakes of the type such as the lower Madison lakes which have received very large amounts of phosphorus should show the greatest overall release of phosphorus from the sediments due to the much higher wind and organism induced mixing between the sediments and the overlying waters.

The hydraulic residence time model is an oversimplified mathematical representation of the recovery rate of a lake after a reduced phosphorus input and ignores many of the processes which influence the phosphorus content of a lake. However, the apparent correspondence of the observed rate of response of Lake Waubesa and Lake Kegonsa with that predicted by the model is not surprising, since the basic assumptions implicit in the model are generally reasonable in this situation.

First, the model assumes the lake to be a completely mixed system with all input water completely mixing with the total volume of the lake. Furthermore, the phosphorus content is considered to be homogeneously dispersed throughout the lake. These conditions appear to be generally met in Lake Waubesa and Lake Kegonsa. Due to their shallow depth, both lakes are mixed to the bottom by wind action during most of the year. Kluesener (13) found that another Madison lake, Lake Wingra, whose depth is similar to Lake Waubesa and Lake Kegonsa (Table 1), is normally well mixed and displays little vertical or horizontal variation in the phosphorus content. Thus, it is likely that Lake Waubesa and Lake Kegonsa essentially have a uniform phosphorus concentration throughout the lake.

Another basic assumption implicit in the model is that water input is equal to water output. Loss of water to evaporation, ground-water seepage, and the output must therefore be equal to the inflow from tributaries, springs, or precipitation. Based on hydrologic studies of the upper Yahara River basin (4,5,12,20), this assumption is reasonably valid.

That the phosphorus influx from sources other than sewage, such as runoff and precipitation, remains constant over the period considered is also a basic assumption of the natural flushing approach. However, in the case of the 1958 diversion, there was an overwhelming influx of phosphorus from sewage effluent as compared to other sources. Any natural change in the annual influx of nutrient sources would be small compared to the large reduction resulting from diversion. Thus, the phosphorus influx from sources other than sewage effluent can be presumed to have been constant.

Perhaps the most critical assumption of the model is that phosphorus behaves conservatively in the lake system. This means that the residence time of phosphorus in a lake is equal to that of the water (filling time). Certainly, chemical and biological reactions play a major role in determining the mean residence time of phosphorus in a lake and, therefore, the phosphorus residence time can be quite different than the water residence time. Thus, the model represented in Fig. 5, when modified by substituting the residence time of phosphorus for water, should more adequately describe the rate of recovery of a lake from a reduction in the phosphorus loading. The development of this model based on the phosphorus residence time directly from mass balance considerations may be found in Sonzogni, et al. (27) and Vollenweider (28).

A model based on the phosphorus residence time implicitly accounts for the overall, biological, chemical, and physical processes which affect phosphorus in a lake. Because sediments appear to function as a trap for biologically and chemically precipitated phosphorus (sediments also tend to release phosphorus, but the net movement over an annual cycle is apparently from the water to the sediment), the phosphorus residence time can be less than the water residence time (16,18,21). Thus, the rate of response of some lakes to the elimination of a point source of phosphorus may be more rapid than would be predicted from natural flushing.

Unfortunately, the mean phosphorus residence time is difficult to determine and has been estimated for only a few lakes (21), not including Lake Waubesa or Lake Kegonsa. Nevertheless, it apparently may not be necessary to know the phosphorus residence time of these lakes. Because of the short hydraulic residence time of Lake Kegonsa and Lake Waubesa, the main loss of phosphorus probably occurred through the outlet. Loss of phosphorus from biological and chemical precipitation over an annual cycle was likely to have been small compared to the loss to the outlet from two or three complete exchanges of the total lake volume in a year, especially in view of the relatively high phosphorus concentrations in the water. For this reason the residence time of phosphorus should have approached the residence time of water. Thus, the dominant mechanism controlling the phosphorus content of these lakes (on an annual basis) appears to have been natural flushing rather than chemical and biological processes. It is quite possible that natural flushing could be used to predict the response of other shallow, well-mixed highly polluted lakes with a short hydraulic residence time to phosphorus abatement.

TABLE 3.—Estimated Mean Residence Times for Water and Phosphorus for Various Lakes

Lake (1)	Water residence time, in years (2)	Phosphorus residence time, in years (3)	Source (4)
Washington	3.2	0.8	Megard (21)
Minnetonka	25	0.9	Megard (21)
Sebasticook	3.5	1.4	Megard (21)
Norrviken	0.6	0.3	Megard (21)
Clear	6	2	Megard (21)
Mendota	4.8	3.2	Megard (21)
Mendota	4.5	1	Calculated

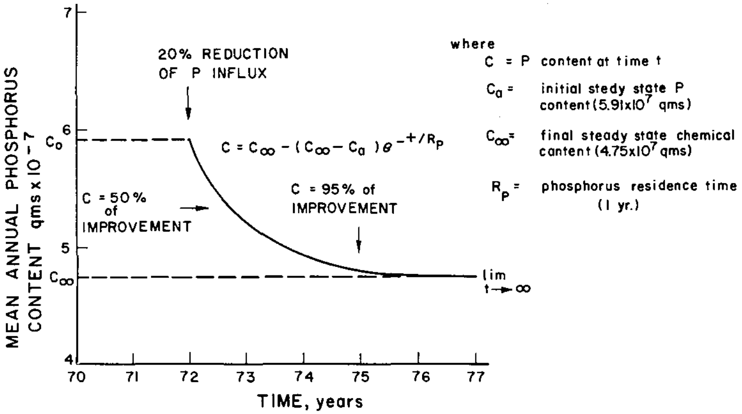

FIG. 6.—Predicted Response of Lake Mendota to Recent Phosphorus Influx Reduction

Rate of Recovery of Lake Mendota to 1971 Diversion.—It has been frequently asked what the effect of the 1971 diversion will be on the water quality of Lake Mendota, especially with regard to the phosphorus level in the lake. Since the hydraulic residence time for Lake Mendota is on the order of 4.5 yr, it can be predicted from natural flushing that it would take about three flushing periods, or about 13.5 yr, from the start of diversion before the lake will equilibrate to the new phosphorus flux, if phosphorus behaves as a conservative element in the lake. However, because it is known that the sediments on an annual basis act as a sink for phosphorus in Lake Mendota (3), the time needed to equilibrate to the new phosphorus flux should be less than 13.5 yr. Thus, the phosphorus residence time is probably quite different from the water residence time, which nullifies a basic assumption of the model based on hydraulic residence time. Also, Lake Mendota, being much deeper than Lake Waubesa or Lake Kegonsa (Table 1), is permanently stratified part of the year, which contradicts the assumption of the hydraulic residence time model that a lake is completely mixed. Therefore, a different model, such as the phosphorus residence time model, should be employed.

The phosphorus residence time for Lake Mendota may be estimated by dividing the mean annual steady state phosphorus content by the annual phosphorus loading (21). The mean annual phosphorus content was determined for 1970–1971 (assuming the content at this time was an equilibrium content) from detailed sampling at nearly weekly intervals. The annual phosphorus loading for Lake Mendota was recently estimated by Sonzogni and Lee (26). Note that the estimated annual phosphorus loading is only a rough approximation, and may vary widely from year to year. Nonetheless, using these data, a mean phosphorus residence time of approx 1 yr is obtained for Lake Mendota, which is lower than the residence time of 3.2 yr reported by Megard (21). The value reported by Megard was apparently arrived at using older and less complete data. However, the residence time of 1 yr as computed from current data agrees surprisingly well with the estimated mean phosphorus residence time of other lakes as shown in Table 3.

If the mean phosphorus residence time is indeed a constant in Lake Mendota, then a new steady-state phosphorus content should be reached approx 3 yr following the start of diversion, as indicated in Fig. 6. Thus, the total phosphorus content is predicted to decrease by approx 20% approx 3 yr after diversion. If the lake were completely mixed and the phosphorus homogeneously dispersed, the concentration of total phosphorus would decrease from about 0.12 mg/l P-R to 0.10 mg/l P, or by about 0.02 mg/l P, as a result of the diversion, assuming that the sediments in Lake Mendota continue to behave primarily as a sink for phosphorus.

Unfortunately, because of the relatively small decrease in the estimated phosphorus loading as a result of the 1971 diversion, it is doubtful that the predicted change in the mean annual phosphorus content will be seen analytically. Normal year to year variability in the loading from other sources, as well as other factors, may overshadow the effect of the diversion. This is not to say that the 1971 diversion was not of value. On the contrary, the diversion served essentially as a preventive measure to avoid future degradation of the water quality of the lake. This degradation could have occurred if wastewater, steadily increasing in amount as a result of a rapidly expanding population on the north and west side of the lake, were to continue to be discharged into the lake.

SUMMARY AND CONCLUSIONS

The effect of wastewater diversions on the water quality of the Madison lakes, as well as on the receiving waters of the diverted effluent, has been reviewed. The most significant diversion occurred in 1958 when treated sewage effluent from Metropolitan Madison was diverted from entering Lake Waubesa. Following this diversion a considerable improvement in Lake Waubesa and a lower lake, Lake Kegonsa, resulted. Based on the rate of change of the winter soluble phosphorus content of Lake Waubesa and Lake Kegonsa, the recovery of these lakes was found to be similar to that predicted from a simple exponential decay model based on the hydraulic residence time of the lakes. For other lakes with longer hydraulic residence times than Lake Waubesa or Lake Kegonsa, such as Lake Mendota, a model based on the phosphorus residence time should more accurately predict the rate of response to a decreased phosphorus input.

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

C = chemical concentration at any time;
C_0 = concentration in lake at time = 0;
C_∞ = concentration in lake at time = ∞;
R = hydraulic residence time;
R_p = phosphorus residence time; and
t = time.

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KEY WORDS: **Algal control;** Diversion; **Environmental engineering; Eutrophication; Hydraulic models; Lakes;** Nutrients; Phosphorus; Sediments; Sewage; **Waste water; Water pollution;** Water quality; **Wisconsin**

ABSTRACT: In general, an improvement in water quality of the Madison, Wisconsin lakes resulted after sewage effluent was diverted from them. This was evidenced by a reduction in the phosphorus content of the lakes as well as a decrease in the frequency and severity of blue-green algal blooms. Based on the limited data available, the rate of response of two relatively small and shallow Madison lakes, Lake Waubesa and Lake Kegonsa, following a reduced phosphorus influx (the result of a major sewage diversion in 1958) was found to be similar to that predicted from a simple, exponential decay model based on the hydraulic residence time. It is predicted based on a phosphorus residence time that a new equilibrium phosphorus content will be reached in Lake Mendota in about 1975, or about three years following the reduction in the phosphorus resulting from resulting from the wastewater diversion.

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