

NUTRIENT BUDGET AND ITS CRITICAL EVALUATION  
FOR THE FOX CHAIN OF LAKES

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ABSTRACT

The Fox Chain of Lakes receives approximately 6370 kg/day of total nitrogen and 730 kg/day of total phosphorus. Of the total phosphorus and total nitrogen, about 130 kg/day of phosphorus and 375 kg/day of nitrogen emanate from point sources of waste discharges. The Fox River transports about 70 percent of inorganic nitrogen, and together with Nippersink and Squaw Creeks contributes about 93 percent of the total inorganic nitrogen. Also, these three tributaries contribute 86 percent of the dissolved orthophosphorus. About 27 percent of total nitrogen and 37 percent of total phosphorus influx into the lake system are retained in the lakes. The impacts of septic tank systems and precipitation were found to be equal as far as total phosphorus is concerned. The net loading rates, considering only the readily available nitrogen and phosphorus retained in the lakes, were found to be 17.4 g/m<sup>2</sup>/yr and 1.5 g/m<sup>2</sup>/yr, respectively, for nitrogen and phosphorus. These loading rates, computed on the basis of lake surfaces, are several orders of magnitude in excess of rates for these nutrients which the lakes could absorb without showing the symptoms of eutrophication. It is estimated that phosphorus recycled from the sediments in deep water areas of the Fox Chain alone appears to be adequate for sustaining algal blooms for a long period of time.

INTRODUCTION

The Fox Chain of Lakes consists of nine major internally connected lakes located in Lake and McHenry Counties in northern Illinois. The main inflow into the lake system is the Fox River. Other tributaries of importance are the Sequoit, Nippersink, and Squaw Creeks, and Lily Lake Drain.

The lakes and their associated shorelands constitute a valuable natural resource that is showing the effects of increased cultural pressure exerted on them. The shores of these lakes were first dotted by summer homes but these have long been converted to year-round occupancy. All of the shore naturally suitable for construction of homes, restaurants, marinas, and other recreational facilities has been developed. Artificial channels have been dredged to accommodate demands for lake frontage property. The recreational value of the lakes is a major economic influence in the area.

Nuisance algal blooms have been a source of recorded complaints on the Chain for at least the past 35 years. Such protests expressed apprehensions regarding the curtailment of bathing, fishing, lowering of property values, cancellation of resort trade, and impairment of the picturesque beauty of the Chain.

It is generally recognized that there is an urgent need for the development and implementation of technically sound and economically feasible management plans for controlling the accelerated eutrophic conditions in the lakes. As a prerequisite for this management plan, it is imperative to identify the sources and magnitude of the nutrients influx into the lakes. Details of the nutrient budget developed for the Fox Chain of Lakes and a critical evaluation of the nutrient balance for the lake system are reported here.

#### NUTRIENT BUDGET

Though nitrogen and phosphorus are not the only nutrients required for algal growth, they are generally considered to be the two main nutrients involved in the lake eutrophication process. In spite of the controversy over the role of carbon as a limiting nutrient, a vast majority of the researchers regard phosphorus as the most frequently limiting nutrient in lakes (Bartsch, 1972; Gakstatter et al., 1975; Malueg et al., 1973; U. S. Environmental Protection Agency, 1973; and Vollenweider, 1968).

Several factors have complicated attempts to quantify the relationship between lake trophic status and measured nutrient concentrations of the lake waters. For example, measured inorganic nutrient concentrations do not denote nutrient availability to the plant, but merely represent what is left over by the lake production process. A certain fraction of the nutrients (particularly phosphorus) while passing through successive biological cycles becomes refractory. In addition, numerous morphometric and chemical factors affect the availability of nutrients in lakes. Factors such as mean depth, basin shape, and detention time affect the amount of nutrients a lake can absorb without developing nuisance conditions. Nutrient budget calculations represent the first step in quantifying the dependence of lake water quality on the nutrient supply. It is often essential to quantify the sources of nutrients from management and eutrophication control viewpoints. Thus Vollenweider (1968) and

others have emphasized the importance of quantifying nutrient supply, particularly those of nitrogen and phosphorus, in determining lake trophic status.

Potential sources of nitrogen and phosphorus for lakes are the watershed drainage which can include agricultural runoff, urban runoff, swamp and forest runoff, domestic and industrial waste discharges, septic tank discharges from lakeshore developments, precipitation on lake surface, dry fallouts (i.e., leaves, dust, seeds, and pollen), groundwater influxes, nitrogen fixation, sediment recycling, and aquatic bird and animal wastes. Potential sinks can include outlet losses, fish catches, aquatic plant removal, denitrification, groundwater recharge, and sediment losses. Some sources and sinks, e.g., groundwater, nitrogen fixation and denitrification, and nitrogen and phosphorus recycling from sediments, require elaborate sampling and experimental procedures for adequate evaluation. Consequently, manpower and time constraints have resulted in less than complete nutrient balance studies reported thus far.

A partial nitrogen and phosphorus budget is presented here. The budgets are referred to as 'partial' since no attempt was made to account for such sources of nitrogen and phosphorus as groundwater, leaves, pollen, seeds, or nitrogen fixation.

Nutrient emissions from municipal and industrial waste treatment plants in Illinois, contributing to the lake system either directly or through tributaries, were estimated by assessing the effluent quality characteristics. The nutrients transported by the Fox River and other tributaries to the Fox Chain of Lakes were measured by determining the weekly phosphorus and nitrogen concentrations in the streams in conjunction with the streamflow rates. Because the sampling sites were located on the tributaries close to the lakes, nutrient transport values estimated for the tributaries combine the contributions of point and non-point sources. Thus, knowing the total nutrient transport of the streams, and the municipal and industrial wasteflow contributions, the magnitude of nonpoint sources contribution could be estimated by difference. Nutrient contributions from precipitation were determined from phosphorus and nitrogen concentrations of rainwater samples collected periodically at three sampling sites in the area and from the total annual precipitation for the area. Figure 1 shows the Fox Chain of Lakes, its major tributaries, municipal waste discharges within the Illinois portion of the Chain's watershed, and tributary and rainwater sampling points.

The nutrient contribution from groundwater is considered to be insignificant compared with other sources. In nearby Cedar Lake (shown in Figure 1) which is entirely springfed, the nitrogen concentrations were found to be comparable to those found in the Fox Chain of Lakes. However, the phosphorus concentrations in Cedar Lake were much less. This was true even in the hypolimnetic zone of Cedar Lake which was anoxic during summer months.



TABLE 1. Rainwater Quality Characteristics at Four Locations in Illinois  
(Concentrations in mg/l)

| Location                  | Number of analyses | Mean | Range      |
|---------------------------|--------------------|------|------------|
| <i>Nitrate-N</i>          |                    |      |            |
| Antioch                   | 11                 | 0.77 | 0.26-2.90  |
| Chain of Lakes State Park | 8                  | 0.81 | 0.32-1.58  |
| Lake Villa                | 16                 | 1.11 | 0.37-2.43  |
| Peoria                    | 6                  | 0.53 | 0.30-0.85  |
| <i>Kjeldahl-N</i>         |                    |      |            |
| Antioch                   | 9                  | 2.88 | 0.65-5.01  |
| Chain of Lakes State Park | 3                  | 5.45 | 1.81-11.10 |
| Lake Villa                | 9                  | 2.53 | 0.85-6.03  |
| Peoria                    | 3                  | 0.86 | 0.46-1.22  |
| <i>Ammonia-N</i>          |                    |      |            |
| Antioch                   | 11                 | 2.22 | 0.38-4.78  |
| Chain of Lakes State Park | 8                  | 1.97 | 0.32-5.67  |
| Lake Villa                | 14                 | 1.90 | 0.40-4.82  |
| Peoria                    | 6                  | 0.68 | 0.34-1.07  |
| <i>Total phosphorus</i>   |                    |      |            |
| Antioch                   | 11                 | 0.27 | 0.12-0.64  |
| Chain of Lakes State Park | 8                  | 0.32 | 0.00-0.70  |
| Lake Villa                | 14                 | 0.56 | 0.03-2.09  |
| Peoria                    | 5                  | 0.17 | 0.04-0.41  |

7.41, 16.92, and 3.18, respectively. The Fox Chain of Lakes with a total surface area of about 2772 hectares receive annually 20,227 kg of nitrate, 46,893 kg of ammonia, and 8844 kg of total phosphorus from direct precipitation.

#### Contributions from Septic Tanks

Septic tank field-tile systems are generally a problem only if they become clogged or water-bound which is likely to occur in non-sandy soils such as the types found in the Fox Chain of Lakes area. When this occurs, surface discharge results, and nutrients in the effluent can be transported via overland flow to the lakes. Local residents have reported such occurrences that are apparent in winter under snow-cover conditions.

In the absence of detailed field measurements to quantify the nutrient contribution to the lakes from septic systems, an indirect approach in estimating the nutrient contribution was taken here. There are about 6900 residential units around the lakes that use septic systems, and

institutions like schools, churches, hotels, restaurants, and other commercial enterprises contribute an estimated daily wasteflow of 590 cubic meters. This wasteflow is equivalent to that flow from a population of 1550 persons at the rate of 0.38 cubic meter per capita per day. Further, assuming an average occupancy of three persons per residential unit, the total number of humans contributing to wasteflow could be 22,250. Therefore, the assumption here is that 22,250 persons are served by septic tanks.

Phosphorus and nitrogen contribution rates, in terms of kilograms per capita per year (kg/cap/yr), used in estimating the impact of septic tank systems by different investigators have differed significantly. Sonzogni and Lee (1972) used rates of 1.36 kg/cap/yr for soluble orthophosphorus; 2.04 kg/cap/yr for total phosphorus; 2.72 kg/cap/yr for inorganic nitrogen; and 3.63 kg/cap/yr for total nitrogen in estimating septic tank contributions to Lake Mendota in Wisconsin. The U. S. Environmental Protection Agency (1973) recommends rates of 1.50 kg/cap/yr for total phosphorus and 6.49 kg/cap/yr for total nitrogen with the suggestion to reduce these values to account for seasonal occupancy, lack of laundry facilities, and other factors. The rates used by Sonzogni and Lee for Lake Mendota were used in this investigation to evaluate the impact of septic tank disposal systems.

The McHenry County Public Health Administrator estimates that about 10 to 20 percent of the septic tank systems in the Pistakee Lake area could be malfunctioning (William Mellon and Richard Wissell, personal communication, 1976). If a failure rate of 20 percent was used for the entire Fox Chain of Lakes area, the amount of nitrogen and phosphorus added to the Fox Chain of Lakes from malfunctioning units is estimated to be: inorganic nitrogen, 12,110 kg/yr; total nitrogen, 16,145 kg/yr; dissolved orthophosphorus 6080 kg/yr; and total phosphorus 9070 kg/yr.

#### Nutrient Balance

An inventory of nutrient emissions to the Fox Chain from major point sources within Illinois is shown in Table 2. The average emission rates in terms of kilograms per day for ammonia, nitrate, organic nitrogen, dissolved orthophosphorus, and total phosphorus are shown in this table. Total inorganic nitrogen and dissolved orthophosphorus, which are the readily available forms of plant nutrients discharged by the Woodstock northside treatment plant, were the highest among the observed values. These were followed by the discharges from the Round Lake Sanitary District waste treatment plant.

Table 3 shows the nutrient loads transported by the Fox River and other tributaries to the Fox Chain of Lakes. The nutrient loads transported by the streams are further classified as to point or nonpoint sources. Because no detailed inventory of point nutrient sources in Wisconsin was made, the nutrients transported by the Fox River into the Fox Chain of Lakes are all shown as from nonpoint sources. The relative importance of point sources and nonpoint sources in nitrogen and phosphorus contributions is also shown in the table.

TABLE 2. Inventory of Point-Source Nutrient Emissions

| Treatment plant                    | Mean<br>flow<br>(mgd) | Mean<br>concentration<br>(mg/L) | Load<br>(kg/day) |
|------------------------------------|-----------------------|---------------------------------|------------------|
| <i>Ammonia-N</i>                   |                       |                                 |                  |
| Hebron Trickling<br>Filter Plant   | 0.10                  | 10.05                           | 3.80             |
| Hebron Lagoons                     | 0.09                  | 6.91                            | 2.35             |
| Richmond                           | 0.15                  | 8.69                            | 4.93             |
| Woodstock North-<br>side Plant     | 2.00                  | 13.05                           | 98.72            |
| Woodstock Die<br>Casting Company   | 0.55                  | 0.19                            | 0.39             |
| Lake Villa                         | 0.15                  | 4.68                            | 2.65             |
| Round Lake Sani-<br>itary District | 1.60                  | 15.15                           | 91.68            |
| Antioch                            | 0.75                  | 5.84                            | 16.56            |
| Fox Lake                           | 0.25                  | 14.08                           | 13.32            |
| <i>Nitrate-N</i>                   |                       |                                 |                  |
| Hebron Trickling<br>Filter Plant   | 0.10                  | 11.95                           | 4.52             |
| Hebron Lagoons                     | 0.09                  | 1.03                            | 0.35             |
| Richmond                           | 0.15                  | 4.79                            | 2.72             |
| Woodstock North-<br>side Plant     | 2.00                  | 0.55                            | 4.16             |
| Woodstock Die<br>Casting Company   | 0.55                  | 1.70                            | 3.54             |
| Lake Villa                         | 0.15                  | 4.19                            | 2.38             |
| Round Lake Sani-<br>itary District | 1.60                  | 0.56                            | 3.39             |
| Antioch                            | 0.75                  | 5.17                            | 14.76            |
| Fox Lake                           | 0.25                  | 1.60                            | 1.51             |
| <i>Organic-N</i>                   |                       |                                 |                  |
| Hebron Trickling<br>Filter Plant   | 0.10                  | 9.06                            | 3.43             |
| Hebron Lagoons                     | 0.09                  | 12.41                           | 4.23             |
| Richmond                           | 0.15                  | 3.86                            | 2.19             |
| Woodstock North-<br>side Plant     | 2.00                  | 4.06                            | 30.73            |
| Woodstock Die<br>Casting Company   | 0.55                  | 1.84                            | 3.83             |
| Lake Villa                         | 0.15                  | 2.71                            | 1.54             |
| Round Lake Sani-<br>itary District | 1.60                  | 9.32                            | 56.45            |
| Antioch                            | 0.75                  | 5.40                            | 15.33            |
| Fox Lake                           | 0.25                  | 6.14                            | 5.81             |

(Concluded on next page)

TABLE 2. Concluded

| Treatment plant                   | Mean<br>flow<br>(mgd) | Mean<br>concentration<br>(mg/l) | Load<br>(kg/day) |
|-----------------------------------|-----------------------|---------------------------------|------------------|
| <i>Total phosphorus</i>           |                       |                                 |                  |
| Hebron Trickling<br>Filter Plant  | 0.10                  | 13.54                           | 5.12             |
| Hebron Lagoons                    | 0.09                  | 3.83                            | 1.30             |
| Richmond                          | 0.15                  | 9.24                            | 5.24             |
| Woodstock North-<br>side Plant    | 2.00                  | 7.56                            | 57.19            |
| Woodstock Die<br>Casting Company  | 0.55                  | 2.82                            | 5.87             |
| Lake Villa                        | 0.15                  | 7.02                            | 3.98             |
| Round Lake Sani-<br>tary District | 1.60                  | 5.09                            | 30.80            |
| Antioch                           | 0.75                  | 5.91                            | 16.77            |
| Fox Lake                          | 0.25                  | 7.11                            | 6.72             |
| <i>Dissolved orthophosphorus</i>  |                       |                                 |                  |
| Hebron Trickling<br>Filter Plant  | 0.10                  | 10.50                           | 3.97             |
| Hebron Lagoons                    | 0.09                  | 2.68                            | 0.91             |
| Richmond                          | 0.15                  | 5.57                            | 3.16             |
| Woodstock North-<br>side Plant    | 2.00                  | 5.68                            | 42.97            |
| Woodstock Die<br>Casting Company  | 0.55                  | 2.30                            | 4.78             |
| Lake Villa                        | 0.15                  | 4.38                            | 2.49             |
| Round Lake Sani-<br>tary District | 1.60                  | 4.18                            | 25.30            |
| Antioch                           | 0.75                  | 4.37                            | 12.39            |
| Fox Lake                          | 0.25                  | 4.83                            | 4.57             |

Nutrient flux from major sources to the Fox Chain of Lakes is shown in Table 4. Rates of transport in metric tons per year for ammonia, nitrate total nitrogen, dissolved orthophosphorus, and total phosphorus are listed. Tributaries to the Fox Chain, direct waste discharge, impact of septic tank disposal systems, and precipitation were the major sources of nutrients considered in this investigation. The sum of the first eight items in the list indicates the annual gross loading rates of nutrients. Data pertaining to the Fox River at Johnsburg indicate the magnitude of nutrients transported away from the Fox Chain. The difference between the gross loading rate and the nutrients carried away from the Chain of Lakes represents the amount of nutrients retained by the lakes or the net loading rate of nutrients to the lake system. It is seen that about 27 percent of total nitrogen and 37 percent of total phosphorus applied to the system are retained in the lake system.

TABLE 3. Nutrient Loads Transported by the Fox River  
and Other Tributaries  
(Nutrient loads in kilograms per day)

|                        | Ammonia-N    |                 | Nitrate-N    |                 | Total nitrogen |                 |
|------------------------|--------------|-----------------|--------------|-----------------|----------------|-----------------|
|                        | Point source | Nonpoint source | Point source | Nonpoint source | Point source   | Nonpoint source |
| <i>Inflow</i>          |              |                 |              |                 |                |                 |
| Fox River at Route 173 |              | 458             |              | 2428            |                | 4932            |
| Lily Lake Drain        |              | 1.4             |              | 6.3             |                | 20              |
| Nippersink Creek       | 110          | 20              | 15           | 606             | 170            | 2917            |
| Sequoit Creek          | 17           | 7.7             | 15           | 9               | 47             | 21              |
| Squaw Creek            | 94           | 1.4             | 6            | 70              | 158            | 102             |
| Total nutrient inflow  | 221          | 488             | 36           | 3120            | 375            | 5991            |
| Percentage*            | 3.5          | 7.7             | 0.6          | 49.0            | 5.9            | 94.1            |
| <i>Outflow</i>         |              |                 |              |                 |                |                 |
| Fox River at Johnsburg |              | 631             |              | 2149            |                | 4863            |

|                        | Diss. orthophos. |                 | Total phosphorus |                 |
|------------------------|------------------|-----------------|------------------|-----------------|
|                        | Point source     | Nonpoint source | Point source     | Nonpoint source |
| <i>Inflow</i>          |                  |                 |                  |                 |
| Fox River at Route 173 |                  | 194             |                  | 538             |
| Lily Lake Drain        |                  | 0.2             |                  | 0.8             |
| Nippersink Creek       | 56               | 1.8             | 75               | 26              |
| Sequoit Creek          | 12               | 2.7             | 17               | 11              |
| Squaw Creek            | 28               | 21              | 35               | 24              |
| Total nutrient inflow  | 96               | 216             | 127              | 601             |
| Percentage*            | 13.2             | 29.7            | 17.4             | 82.6            |
| <i>Outflow</i>         |                  |                 |                  |                 |
| Fox River at Johnsburg |                  | 231             |                  | 496             |

\*Computed with respect to total nitrogen or total phosphorus

The relative importance of the various sources of nutrient input is presented in Table 5. In addition to the values for ammonia nitrogen and nitrate-nitrogen, percentage figures for total inorganic nitrogen are also given. These represent the readily available form of nitrogen for biological processes. The Fox River transports about 70 percent of inorganic nitrogen, and together with Nippersink and Squaw Creeks contributes about 93 percent of the total inorganic nitrogen. Also, these three streams

TABLE 4. Nutrient Balance for Fox Chain of Lakes  
(Rates in metric tons per year)

|                           | Ammonia-N | Nitrate-N | Total<br>nitrogen | Diss.<br>orthophos. | Total<br>phosphorus |
|---------------------------|-----------|-----------|-------------------|---------------------|---------------------|
| <i>Inflow</i>             |           |           |                   |                     |                     |
| Fox River<br>at Route 173 | 167.1     | 886.3     | 1800.0            | 70.8                | 196.5               |
| Lily Lake Drain           | 0.5       | 2.4       | 7.4               | 0.1                 | 0.3                 |
| Nippersink Creek          | 47.3      | 226.9     | 396.6             | 19.7                | 36.9                |
| Sequoit Creek             | 9.0       | 8.6       | 24.3              | 5.4                 | 10.1                |
| Squaw Creek               | 34.9      | 27.8      | 94.9              | 17.7                | 21.7                |
| Fox Lake                  | 4.9       | 0.5       | 7.5               | 1.6                 | 2.4                 |
| Treatment Plant           |           |           |                   |                     |                     |
| Septic tank systems       | 6.1*      | 6.1*      | 16.1              | 6.1                 | 9.1                 |
| Precipitation             | 46.9      | 20.2      | 102.7             | 4.4**               | 8.9                 |
| Gross loading rate        | 316.8     | 1178.9    | 2449.6            | 125.9               | 285.8               |
| <i>Outflow</i>            |           |           |                   |                     |                     |
| Fox River<br>at Johnsburg | 230.3     | 783.7     | 1774.9            | 94.3                | 181.0               |
| Net loading rate          | 86.5      | 394.6     | 674.6             | 41.6                | 104.9               |
| Percentage retained       | 27.3      | 33.5      | 27.5              | 33.1                | 36.7                |

\*Assumed inorganic nitrogen equally divided

\*\*Assumed dissolved orthophosphorus 50 percent of total phosphorus

TABLE 5. Relative Importance of External Sources  
of Nutrients, in Percent

|                           | Ammonia-N | Nitrate-N | Total<br>inorganic<br>nitrogen | Total<br>nitrogen | Diss.<br>orthophos. | Total<br>phosphorus |
|---------------------------|-----------|-----------|--------------------------------|-------------------|---------------------|---------------------|
| Fox River<br>at Route 173 | 52.8      | 75.2      | 70.4                           | 73.5              | 56.3                | 68.7                |
| Lily Lake Drain           | 0.0       | 0.0       | 0.2                            | 0.0               | 0.0                 | 0.1                 |
| Nippersink Creek          | 14.9      | 19.3      | 18.3                           | 16.2              | 15.6                | 12.9                |
| Sequoit Creek             | 2.8       | 0.7       | 1.2                            | 1.0               | 4.3                 | 3.5                 |
| Squaw Creek               | 11.0      | 2.4       | 4.2                            | 3.9               | 14.0                | 7.6                 |
| Fox Lake                  | 1.5       | 0.0       | 0.4                            | 0.3               | 1.3                 | 0.9                 |
| Treatment Plant           |           |           |                                |                   |                     |                     |
| Septic tank<br>systems    | 1.9       | 0.5       | 0.8                            | 0.7               | 4.8                 | 3.2                 |
| Precipitation             | 14.8      | 1.7       | 4.5                            | 4.2               | 3.5                 | 3.1                 |

contribute about 86 percent of the dissolved orthophosphorus with the Fox River applying about 56 percent. The impact of septic tank systems and precipitation appears to be equal as far as total phosphorus is concerned. Each contributes about 3 percent of the total.

## DISCUSSION

The best available guidelines for relating the nutrient flux to water quality in lakes were first proposed by Vollenweider (1968). These guidelines were used subsequently by several investigators (Bartsch, 1972 and Gakstatter et al., 1975). According to Vollenweider, for lakes with mean depths of 5 meters (16.4 feet) or less, permissible loading levels of biochemically active nitrogen and phosphorus are, respectively, 1.0 and 0.07 g/m<sup>2</sup>/yr. For the same average depth, loading rates greater than 2.0 g/m<sup>2</sup>/yr for nitrogen and 0.13 g/m<sup>2</sup>/yr for phosphorus are considered excessive from a eutrophication point of view. The overall mean depth of the Fox Chain of Lakes is 1.74 meters; therefore, the guidelines cited by Vollenweider are applicable to the Chain of Lakes. The loading rates of total inorganic nitrogen and dissolved orthophosphorus for the Chain of Lakes were found to be 54.0 and 4.5 g/m<sup>2</sup>/yr, respectively.

The net loading rates, considering only the available nitrogen and available phosphorus retained in the lakes, were found to be 17.4 and 1.5 g/m<sup>2</sup>/yr, respectively, for nitrogen and phosphorus. It is seen that even the net loading rates of biologically active nitrogen and phosphorus are about ten times greater than the excessive levels of nutrient loading rates suggested by Vollenweider. The total nitrogen and total phosphorus loading rates for Lake Mendota were reported to be 3.10 and 0.17 g/m<sup>2</sup>/yr, respectively, and those for Lake Washington were 31.4 and 1.34 g/m<sup>2</sup>/yr (Vollenweider, 1968). Lake Waubesa in Wisconsin was found to have nutrient loading rates comparable to the rates observed for Fox Chain of Lakes. These three lakes were classified as eutrophic.

The total nitrogen and total phosphorus loading rates contributed to the lakes by the Fox River are 65.0 and 7.1 g/m<sup>2</sup>/yr, respectively. The Fox River inorganic nitrogen and dissolved orthophosphorus loading rates amounted to 38.0 and 2.6 g/m<sup>2</sup>/yr. These loading rates are several orders of magnitude larger than the excessive loading rate suggested by Vollenweider and others. The importance of controlling nutrient influx through the Fox River is apparent. Efforts to minimize eutrophic conditions by controlling all of the other sources without curbing nutrients transported by the Fox River would be futile.

Nutrients entering a lake become incorporated in various chemical and biological cycling processes. Part of the nutrients are utilized in the metabolism of organisms, i.e., phytoplankton, zooplankton, vascular plants, and fish, and on death and decay of the organisms the nutrients are liberated for reuse. Part of the nutrients remain in solution, part become temporarily or permanently incorporated in the bottom sediments, and part flow out of the lakes. Part of the nutrients that accumulate in the lake, after a period of years, become available in concentrations sufficient to support algal blooms.

Organic matter, whether derived from external sources or produced internally, decomposes and oxidizes in the aerobic parts of the lakes. Organic decomposition, during periods of large algal blooms and in anaerobic zones, occurs when the biological production exceeds the oxidizing capacity of the waters. This results in higher concentrations of organic detritus in the bottom sediments of deeper water areas. Highly productive areas as in bays and dug channels, also exhibit accumulations of organic debris.

When anaerobic conditions develop at the sediment-water interface, nutrients contained in the organic debris are released back into the water. Such 'internal loading' varies from one water body to another and may be very high in certain specific cases. Vollenweider concluded, based on his extensive studies of European and North American lakes, that internal loading is a more serious threat to small lakes than to big lakes, whereas external loading plays a more important part in bigger lakes.

Vollenweider (1968) estimated sediment nutrient release rates of 1.2 and 0.01 g/m<sup>2</sup>/day for ammonia and phosphorus, respectively under anaerobic conditions. Fillos and Swanson (1975) reported phosphorus release rates of 1.2 and 26.0 mg/m<sup>2</sup>/day under aerobic and anaerobic conditions, respectively, for the Lake Warner, Massachusetts, sediment samples. Sridharan and Lee (1974) reported from laboratory leaching experiments with Green Bay (Lake Michigan) sediment samples that release rates of orthophosphorus under anaerobic conditions were much higher than the rates of release under aerobic conditions. They also found that the leaching rates were inversely affected by the presence of orthophosphorus in the leaching medium. They further postulated that the anoxic orthophosphorus release resulted from chemical reactions which are most likely abiotic.

Nutrient release, particularly that of phosphorus from sediment, appears to have a significant bearing on the productivity of lakes especially those that experience thermal stratification. Peterson et al. (1974) reported on a lake restoration experience with Snake Lake in Wisconsin. Dilution and flushing of the lake basin was tried as a restoration technique, by induction of low nutrient groundwater flow. They established that the equilibration with lake bottom sediments could easily supply the dissolved nutrients observed in the lake and concluded that dilution coupled with other management techniques like nutrient inactivation, dredging, etc., may be necessary to achieve long-lasting satisfactory results.

Anoxic conditions in the Fox Chain of Lakes exist in the areas where the depth of water columns exceeds 4.58 meters. From the depth-area relationships developed for the lakes, the areal extent of the lake system with water depths greater than 4.58 meters at normal pool level was estimated as 178 hectares. Assuming a phosphorus release rate of 10 mg/m<sup>2</sup>/day (Vollenweider, 1968) under anaerobic conditions, the amount of phosphorus released from the sediments to the overlying waters during the 5-month period of thermal stratification is estimated to be  $2.673 \times 10^6$  grams or

approximately 5900 pounds. This alone results in a phosphorus loading rate of  $0.1 \text{ g/m}^2/\text{yr}$  for the entire lake system. The loading rate approaches the excessive loading rate from eutrophication viewpoint suggested by Vollenweider (1968). Phosphorus recycled from the sediments in deep water areas of the Fox Chain of Lakes alone appears to be adequate for sustaining algal blooms for a long period of time.

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