Source, Movement, and Effects of Nitrogen and Phosphorus in Three Ponds in the Headwaters of Hop Brook, Marlborough, Massachusetts

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4017

Prepared in cooperation with the

COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF ENVIRONMENTAL QUALITY ENGINEERING
DIVISION OF WATER POLLUTION CONTROL

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By John C. Briggs and William D. Silvey

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

The following factors can be used to convert inch-pound units to International System of Units (SI).

Multiply inch-pound units	By	To obtain SI Units
	Length	
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	square hectometer (hm^2)
	Volume	
acre-foot (acre-ft)	1233	cubic meter (m^3)
	Volume per unit time (includes flow)	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound (lb)	0.4536	kilogram (kg)
	Specific Conductance	
micromho per centimeter at 25°C (μmho/cm at 25°C)	1.000	microsiemens per centimeter at 25°C (μS/cm at 25°C)

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ABSTRACT

The headwaters of Hop Brook near Marlborough, Massachusetts, contain a series of three in-line ponds--Hager Pond, Grist Millpond, and Carding Millpond--that receive over half of their surface-water inflow as effluent from the Marlbrorough Easterly Wastewater Treatment Plant. These ponds have a history of summer algal blooms and fish kills. Water entering these ponds contains quantities of nitrogen and phosphorus far higher than the levels known to promote excessive growth of aquatic vegetation. As the water moves through the three ponds, nitrogen levels decrease. Although some nitrogen is lost to the atmosphere by denitrification, the bulk of the nitrogen probably is retained in the pond sediments. There is a net decrease in phosphorus in the water leaving Carding Millpond compared to the water entering Hager Pond. However, during most sampling periods, the phosphorus concentration of water leaving Carding Millpond is still above the level known to cause excessive growth of aquatic vegetation in lakes. During certain summer periods, there appears to be release of some phosphorus from the sediments in Carding and Grist Millponds. No improvement in water quality of the three ponds can be expected until the concentrations of nutrients entering Hager Pond are reduced to levels that will not support excessive growth of aquatic vegetation.

INTRODUCTION

Three in-line ponds, Hager Pond, Grist Millpond, and Carding Millpond, lie in the headwaters of Hop Brook near Marlborough, Massachusetts. During the summer months, these ponds have experienced nuisance growths of algae and low dissolved-oxygen concentrations. An excessive quantity of algae is aesthetically unpleasant to area residents and causes low dissolved-oxygen concentrations with resultant fish kills. Effluent that is rich in plant nutrients has been discharged from the Marlborough Easterly Wastewater Treatment Plant into an unnamed tributary to the most upstream pond--Hager Pond--since the treatment plant was built in 1896.

The wastewater treatment plant has undergone extensive modification and expansion in an effort to improve the water quality within the ponds and to meet the needs of an expanding population. Secondary or biological treatment, including the construction of trickling filters and Imhoff tanks, was put into operation in 1946. Tertiary treatment, including the complete conversion of ammonia nitrogen to nitrate nitrogen through forced aeration, year-round removal of phosphorus, and chlorination of the final effluent, was added in phases begining in 1973, with full operation in 1975.

Waters receiving effluent from the plant have been examined by several Federal and State agencies. During 1965, the Massachusetts Department of Public Health conducted a sanitary survey of the receiving waters. From 1972 until early 1973, the USEPA (U.S. Environmental Protection Agency) included Hager Pond in the National Eutrophication Survey (U.S. Environmental Protection Agency, 1975). Also in 1973, the MDWPC (Massachusetts Division of Water Pollution Control) conducted an intensive chemical and biological study of the in-line ponds during the summer months (Massachusetts Division of Water Pollution Control, 1974).

A major concern of the MDWPC has been whether the pond system, which receives the effluent from the wastewater treatment plant, was responding to the reduced concentrations of nitrogen and phosphorus after the initiation of tertiary treatment. It was hoped that tertiary treatment would improve the water-quality conditions within the ponds.

Purpose and Scope

This report, prepared by the U.S. Geological Survey in cooperation with MDWPC, presents the results of a study, begun in 1976, of the occurrence and movement of plant nutrients within the series of ponds.

Specific objectives of the report are to: (1) Describe the sources of nitrogen and phosphorus in the system of ponds; (2) describe the movement of the nitrogen and phosphorus through the system of ponds; (3) describe the water quality of the system using algal growth potential and enumeration and identification of phytoplankton; and (4) estimate the future water-quality condition of the ponds.

Acknowledgments

Thanks are extended to the members of the Massachusetts Division of Water Pollution Control, Technical Services Branch, and to John Hartley who supervises the operation of the Marlborough Easterly Wastewater Treatment Plant for the City of Marlborough, Massachusetts, for their cooperation and assistance during the study.

DESCRIPTION OF THE STUDY AREA

The study area is located in eastern Massachusetts, about 22 miles west of Boston, in Middlesex County, and straddles the eastern corporate boundary of Marlborough. Three small ponds comprising the study area, Hager Pond, Grist Millpond, and Carding Millpond (fig. 1), lie in the headwaters of Hop Brook. The ponds drain from one to the other and into Hop Brook which is in the Merrimack River basin. The topography of the area has been modified by glaciers. Much of the area, including the bottom of the ponds, is covered by up to 28 feet of unconsolidated sands and gravels that were laid down in unnamed glacial lakes near Marlborough or as part of glacial Lake Sudbury (Nelson, 1974). Higher areas contain mostly unstratified and poorly sorted deposits of till. Bedrock underlying the study area is mostly igneous rock that ranges from quartz monzonite to quartz diorite. Principal minerals in the bedrock are quartz, perthite and microcline, plagioclase, biotite, muscovite, epidote, and hornblende (Nelson, 1975). The drainage basin generally consists of forests in higher areas and wetlands in lower areas. Relatively few homes have been built within the drainage basin, however, those present are on large lots.

As discussed later in the report, the effluent from the wastewater treatment plant constitutes 50 percent or more of the inflow to Hager Pond during much of the year. Hager Pond is about 25 acres in area, has a mean depth of 5 feet, and contains about 124 acre-feet of water (U.S. Environmental Protection Agency, 1975). Outflow from Hager Pond enters the smaller, elongated Grist Millpond, which has a surface area of about 12.5 acres. Grist Millpond drains into Carding Millpond, which is the largest of the three ponds, with a surface area of 31 acres. MDWPC (1980) reports a mean depth of 2.5 feet for Hager Pond, 2.1 feet for Grist Millpond, and 1.7 feet for Carding Millpond. From Carding Millpond, Hop Brook flows into Sterns Millpond, which was not included in the study.

A time-of-travel study, conducted by MDWPC on December 4-5, 1973 (Paul Hogan, MDWPC, written commun., 1980), determined that the leading edge of the dye used as a tracer took 6.75 hours to pass from the inlet to the outlet of Hager Pond, 19 hours to travel from the outlet of Hager Pond to the Outlet of Grist Millpond, and 22 hours from the outlet of Grist Millpond to the outlet of Carding Millpond. No measurement of streamflow was made during the time-of-travel study, however, records from Boulder Brook at East Bolton (U.S. Geological Survey, 1975 and 1980), which is about 8 miles northwest of Hager Pond, were used to estimate a discharge of 3 to 3.5 ft^3/s at the outlet of Hager Pond during the time-of-travel study.

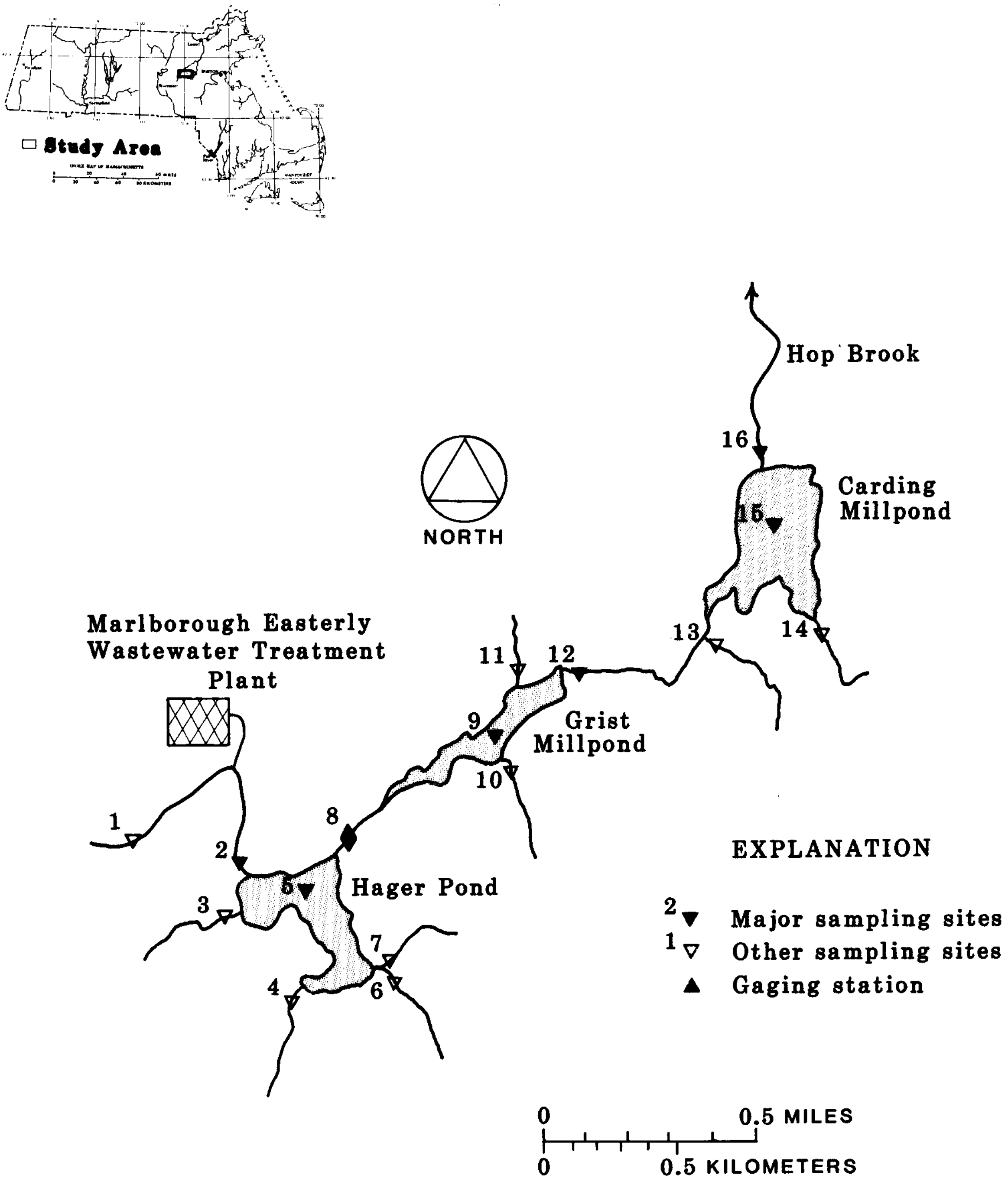

Figure 1.--Study area showing pond system, sampling sites, and wastewater treatment plant.

METHODS OF STUDY

Sampling locations are listed by site name and number in table 1 and are identified by number in figure 1. Sites were chosen to measure all surface-water inflow and outflow from the individual ponds. The seven major sampling sites had a seasonal sampling frequency which was approximately bimonthly from April through November during the study. That frequency was chosen to represent the beginning of the algal growing season, the spring maximum, the late summer period, and the fall die-off. Major sampling sites were established where there were the largest flows and on the ponds themselves. Site 2, Hager Pond tributary, which includes the effluent from the wastewater treatment plant, was sampled just upstream from where it enters Hager Pond. This tributary is the major source of water to the three-pond system. Hager Pond, site 5, was sampled midway between the major inflow, site 2, and the outflow, site 8. Grist Millpond and Carding Millpond were also sampled midway between points of major inflow and outflow (sites 9 and 15, respectively) and at their outflows (sites 12 and 16, respectively).

An additional nine sites were sampled only once at a low-flow period in November 1976. During most periods, their flows were not a significant contribution to the pond system.

Table 1.—Sampling sites in the study area

[Major sampling sites are those sampled seasonally; secondary sampling sites are those sampled once.]

Site number	Sampling site and remarks	Sampling frequency
1	Unnamed tributary to Hager Pond. Sampling point is upstream of inflow from treatment plant effluent.	November 1976, only
2	Unnamed tributary to Hager Pond. Sampling point is downstream of inflow of treatment plant effluent.	Seasonal
3	Unnamed tributary to Hager Pond.	November 1976, only
4	Unnamed tributary to Hager Pond.	November 1976, only
5	Hager Pond. Approximate center of pond.	Seasonal
6	Unnamed tributary to Hager Pond.	November 1976, only
7	Unnamed tributary to Hager Pond. No flow at time of sample collection. No sample collected.	November 1976, only
8	Hager Pond Outlet. Inflow to Grist Millpond. Streamflow gaging station.	Seasonal
9	Grist Millpond. Approximate center of pond.	Seasonal
10	Unnamed tributary to Grist Millpond.	November 1976, only
11	Unnamed tributary to Grist Millpond.	November 1976, only
12	Grist Millpond Outlet. Inflow to Carding Millpond.	Seasonal
13	Unnamed tributary to Carding Millpond.	November 1976, only
14	Unnamed tributary to Carding Millpond.	November 1976, only
15	Carding Millpond. Approximate center of pond.	Seasonal
16	Outlet of Carding Millpond. Beginning of Hop Brook.	Seasonal

Characteristics measured at the major sampling sites are shown in table 2. The tributaries to the pond system and the outflows were sampled by fluvial-sediment sampling techniques described by Guy and Norman (1970). Use of these techniques ensured that samples collected for analysis of total constituents contained a representative subsample of both the dissolved and suspended material passing through the stream cross section at the time of sampling. The term "total" applied to a measured constituent means that the sample consisted of a water-suspended sediment mixture and that the analytical method determines all the constituent in the sample. In the ponds, composite samples were collected from the water column using a weighted bottle that was raised and lowered at a constant rate of speed. The lower 1 foot of the water column was not sampled to prevent incorporating any disturbed bottom material into the sample. Collection of a composite sample of the water column was chosen rather than samples at specific depths because of the shallow depth of the three ponds.

Stream-discharge measurements were made with current meters using the techniques described by Carter and Davidian (1968). At the time of sample collection, specific conductance and pH were measured by methods described by Wood (1976), and dissolved-oxygen concentration and temperature were measured in the stream or pond with a dissolved-oxygen meter and techniques described in Skougstad and others (1979). Samples collected for laboratory analyses were preserved in the field and immediately shipped to the Geological Survey laboratory in Atlanta, Georgia, or in Albany, New York. Sample preservation and analytical methods are described in Skougstad and others (1979), Greeson and others (1977), and Greeson (1979).

Table 2.—Characteristics measured at the major sampling sites

Field determinations	Major nutrients	Biological characteristics
Discharge	Nitrogen	Algal growth potential
Water temperature	Total nitrogen	Phytoplankton, enumeration and identification of predominant genera (ponds only)
pH	Total organic nitrogen	
Specific conductance	Total ammonia nitrogen	
Dissolved oxygen	Total nitrite nitrogen	
	Total nitrate nitrogen	
	Phosphorus	
	Total phosphorus	
	Total ortosphosphate	

ADDITIONAL CONSTITUENTS MEASURED DURING THE STUDY

Common constituents:

Calcium, magnesium, sodium, potasium, silica, carbonate, bicarbonate, chloride, sulfate, hardness, and noncarbonate hardness

Trace elements:

Arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, selenium, and zinc

Organic constituents:

Polychorinated biphenyls, polychlorinated napthalenes, aldrin, chlordane, DDD, DDE, DDT, dieldrin, endosulfan, endrin, heptachlor, heptachlor epoxide, lindane, mirex, perthane, and toxaphene

All analytical determinations from samples collected during the study are given in tables 14-16. The following sections are concerned only the measured characteristics that directly influence the nuisance-algal problem in the pond system. Streamflow, nitrogen, phosphorus, phytoplankton, algal growth potential, and other measures of the trophic status of the ponds are discussed in detail. For reading ease, tables of data in the following sections list only the month in which a sample was collected; specific dates for each sample are listed in tables 14-16. During any given sampling period, all sites usually were visited within 2 consecutive days.

STREAMFLOW

A gaging station was established in January 1977 at the outlet of Hager Pond (site 8) to provide a daily record of discharge. Records of daily mean streamflow at the station are included in table 17. In addition, instantaneous streamflow measurements were made at each stream sampling site and are listed in tables 15 and 16. The measured discharges for the major sampling sites are listed in table 3.

During most sampling periods, the flow entering Hager Pond at site 2, listed in table 3, was approximately equal to the amount leaving the system at Carding Millpond outlet. During April 1977 and 1978, the smaller tributaries entering the system provided a significant amount of inflow, as much as 60 percent. These were the only sampling periods when the small tributaries were major contributors to the system.

Table 3.—Instantaneous streamflow, in cubic feet per second, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	4.9	—	2.8	—	4.2	—	4.6
1977							
April	17	—	19	—	31	—	29
June	5.1	—	4.2	—	5.4	—	5.2
August	3.9	—	3.0	—	3.2	—	2.7
October	6.5	—	5.5	—	3.7	—	12
1978							
April	11	—	14	—	22	—	27
June	5.8	—	4.8	—	5.2	—	6.0
July	4.1	—	3.3	—	3.1	—	2.6
August	4.9	—	2.3	—	3.6	—	2.8
November	4.1	—	5.1	—	3.4	—	3.6

[1] See figure 1 for site locations.

The wastewater treatment plant contributes a significant amount of the inflow to the system. Figure 2 illustrates the significance of this contribution. Selected daily average streamflows from the gaging station at Hager Pond Outlet (site 8) are plotted against the daily average percentage of treatment plant effluent in the streamflow at Hager Pond Outlet. Daily average flows of effluent were obtained from the treatment plant operators. Monthly average flows are (table 17). Figure 2 shows that, at flows of about 9 ft^3/s or less from Hager Pond, 50 percent or more of the flow is from the wastewater treatment plant. At flows as low as 2 to 3 ft^3/s, 90 percent or more of the flow is contributed by the plant. During the 1977 and 1978 calendar years, the annual mean discharge at site 8 was 7.3 ft^3/s and 6.3 ft^3/s, respectively. The monthly mean discharge for the summer months, shown in table 17, was considerably less than the annual mean discharge with a low of 2.6 ft^3/s in September 1978.

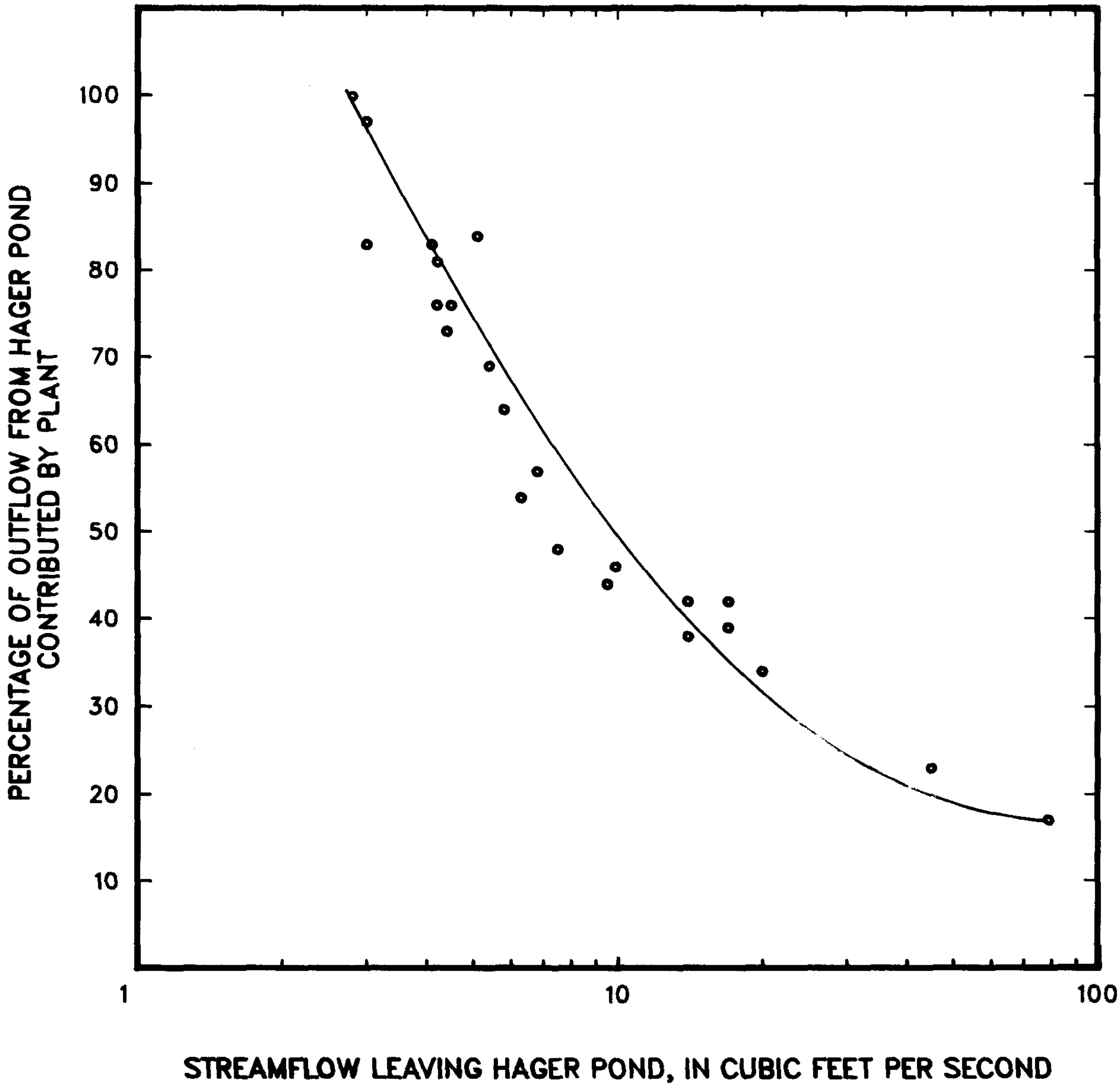

Figure 2.-- Percentage of contribution of wastewater treatment plant effluent to the flow from Hager Pond.

Storage and release of water from the ponds and the large inflow from the wastewater treatment plant helps explain most variations in flow between sites, such as shown in table 3 for the August 1978 sampling period. Flows for the four major streamflow sites (sites 2, 8, 12, and 16) were 4.9, 2.3, 3.6 and 2.8 ft^3/s, respectively. Flow from the wastewater treatment plant varied from 0.2 to 3.5 ft^3/s over the same sampling period. During wet periods, the daily average flow from the wastewater treatment plant was higher, in some instances exceeding 13 ft^3/s. This variation in flow from the treatment plant, coupled with the natural cycles of storage and release of each pond, evapotranspiration, and traveltimes through each pond, could account for the variations in streamflows at the time of sampling.

Losses of pond water to evapotranspiration, evaporation from water surfaces, and transpiration from the plants and trees in or adjacent to the water bodies, could be a significant fraction of the water moving within the ponds during the summer months. Frimpter (1981) shows evapotranspiration at Hyannis, Mass., as high as 5 inches per month during the summer. Using evapotranspiration of 3.5 inches per month as an example, the flow at the Carding Millpond outlet could be reduced by 0.5 ft^3/s. During a particularly dry and hot period, this loss would be higher.

WATER QUALITY

Nitrogen

Different forms of nitrogen were included for analysis in this study (table 2). "Total" in all cases refers to the samples which have not been filtered and are, therefore, composed of both dissolved and suspended particulate material. As mentioned previously, these samples were collected using suspended-sediment sampling techniques to ensure that the sample was representative of both the dissolved and particulate material present in the stream or pond.

The most common nitrogen forms found in water are nitrate, nitrite, ammonia, and organic nitrogen. Organic nitrogen is nitrogen which is included within complex carbon-containing molecules formed by plants and animals. Waste material from plants and animals, as well as their remains after death, are decomposed by bacterial action releasing nitrogen compounds. Organic compounds containing nitrogen are further broken down by bacteria into ammonia. Ammonia is converted by bacteria to nitrite and then into nitrate in the presence of oxygen. This biological conversion of organic and inorganic nitrogen compounds from a reduced state to a more oxidized state is termed "nitrification." Nitrification occurs only when there is a supply of oxygen available.

All forms of nitrogen may enter a lake or pond from a number of sources. These include atmospheric deposition, fixation of elemental nitrogen from the atmosphere by blue-green algae, release of nitrogen from the bottom sediments, input from ground water, and input from the tributaries which enter the pond system. Sources of nitrogen in the waters of tributaries can be either natural, such as leaf material, or man-induced such as agricultural fertilizers or wastewater treatment plant effluents.

The water leaving the pond system can remove nitrogen as either dissolved material or suspended particulate material, such as algae. Nitrogen also may be incorporated into floating and emergent plants in the shallow areas of the ponds. This nitrogen can be released back to the water when the plant dies and decomposes. Nitrogen can be moved from the water column to the bottom sediments by being sorbed to bottom materials or by being incorporated in the bottom sediments when algae or other plant material settles to the pond bottom. However, part of the organic matter on the bottom of shallow ponds may be decomposed and released back into the water. Nitrogen also may be removed by denitrification which proceeds most rapidly under low oxygen conditions and high water temperatures. As dissolved-oxygen levels decrease and approach zero, certain types of bacteria can use the oxygen in the nitrate and nitrite ions as a source of oxygen and, in the process, convert the ions into nitrogen gas. Nitrogen gas can then be lost to the atmosphere or be used by blue-green algae before reaching the atmosphere.

The process of gain and loss of nitrogen within a pond system, as well as the transformation of the forms of nitrogen, is termed the nitrogen cycle. A more complete discussion of the cycle as it applies to aquatic ecosystems is given by Wetzel (1975, chapter 11).

Organic Nitrogen

The values for organic nitrogen at the major sampling sites are listed in table 4. Site 2, which includes the effluent from the wastewater treatment plant, shows a considerable variation in the concentrations of organic nitrogen, which ranged from 0.10 to 2.0 mg/L (milligrams per liter). These concentrations are low for waters containing effluent from a wastewater treatment plant and reflect the treatment process used by the plant to oxidize the organic nitrogen to the nitrate form. For most sampling periods, organic nitrogen remained at about the same concentration throughout the pond system or increased slightly in Carding Millpond and in the water leaving that pond. Blue-green algae, which will be discussed later, were found to predominate in Carding Millpond in the late summer and early fall period, replacing green algae which were dominant earlier. These algae have the ability to "fix" elemental nitrogen; that is, to convert elemental nitrogen into a form usable by the algae as a nutrient source. This adds nitrogen to the system, part of it as organic nitrogen bound up in the algal cell. As the blue-green algae grow, they secrete dissolved organic compounds containing nitrogen. The increase in organic nitrogen seen in Carding Millpond and the outflow from the pond may have been the result of nitrogen fixation by the blue-green algae and release of nitrogen compounds from the decaying remains of green algae.

Table 4.—Concentrations of total organic nitrogen as N, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	0.90	—	1.2	—	—	—	1.5
1977							
April	1.2	1.2	.93	0.98	0.99	0.92	.95
June	2.0	1.2	1.3	.97	1.3	1.7	2.0
August	.10	1.5	2.2	1.9	1.4	1.8	2.1
October	1.2	1.3	1.2	1.4	1.2	1.9	1.8
1978							
April	.86	.59	.53	.53	.41	.47	.28
June	.40	2.0	1.9	1.4	1.7	1.8	.80
July	1.9	1.8	2.2	2.4	2.8	3.1	2.7
August	1.2	3.1	2.4	3.0	1.6	3.0	2.8
November	1.5	1.8	1.7	2.1	1.8	2.2	2.7

[1] See figure 1 for site locations.

Ammonia Nitrogen

Total ammonia nitrogen concentrations in the pond system are shown in table 5. Amounts of ammonia nitrogen entering Hager Pond at site 2 ranged from 0.29 to 0.88 mg/L, while concentrations in Hager Pond ranged from 0.15 to 1.1 mg/L. Ammonia nitrogen concentrations generally decreased when bacteria converted ammonia to nitrite as the water moved through the pond system.

Table 5.--Concentrations of total ammonia nitrogen as N, in milligrams per liter, at the major sampling sites

[Values marked with an asterisk exceed criterion of 0.02 mg/L of un-ionized ammonia nitrogen established for the protection of freshwater aquatic life (U.S. Environmental Protection Agency, 1976).]

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	0.50	—	0.34	—	—	—	0.17
1977							
April	.63	0.44	.57	0.32	0.21	0.08	.15
June	.71	.60	.51	.53	.24	*.36	*.48
August	.31	*.15	*.14	*.21	*.20	.02	.74
October	.47	.75	.66	.33	.18	*.14	.12
1978							
April	.74	.71	.47	.35	.33	.24	.24
June	.52	*.33	*.14	*.38	*.49	*.54	*.50
July	.88	*1.1	*1.5	*.33	*.40	.01	*.05
August	.29	*.95	*.62	*.07	*.42	*.23	*.23
November	.87	.50	.41	.31	.30	*.18	*.23

[1] See figure 1 for site locations.

Although the concentrations of ammonia seem to be low compared to that of nitrate (discussed in a later section of the report), the ammonia concentrations are sufficiently high to cause problems for susceptible fish species living in the lakes. U.S. Environmental Protection Agency (1976) lists a criterion of 0.02 mg/L un-ionized ammonia for protection of freshwater aquatic life. Ammonia dissolved in water forms a chemical equilibrium between un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+). The concentrations shown in table 5 are for both the ionized and the un-ionized forms. The toxicity of ammonia in freshwater systems is attributed to the un-ionized species. Because the equilibrium between ionized and un-ionized ammonia is dependent on pH and temperature, the total ammonia nitrogen value, which was reported, must be mathematically converted to an un-ionized ammonia value. The periods during which the 0.02 criterion was exceeded are shown in table 5.

Nitrite Nitrogen

Concentrations of nitrite nitrogen, which may result from the oxidation of ammonia nitrogen by *Nitrosomonas* bacteria, are shown in table 6. Concentrations of nitrite nitrogen entering the system at site 2 are low; most samples contained less than 0.03 mg/L. During sampling periods in the early spring and late fall, when the pH was near 7, nitrite nitrogen concentrations remained less than 0.1 mg/L throughout the pond system. However, during the summer periods, active algal growth produced an increase in pH to well above 8. Concentrations of nitrite nitrogen may increase during these periods because the bacteria, *Nitrobacter*, which is primarily responsible for oxidizing nitrite to nitrate, is less tolerant of high pH than the bacteria oxidizing ammonia to nitrite. This may have allowed a small accumulation of nitrite in the system. Compared to the concentrations of nitrate nitrogen, however, nitrite nitrogen concentrations remained low at all times.

Table 6.--Concentrations of total nitrite nitrogen as N, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	0.01	—	0.09	—	—	—	0.09
1977							
April	.01	0.03	.04	0.03	0.02	0.01	.03
June	.02	.08	.10	.13	.12	.10	.11
August	.01	.29	.29	.36	.37	.03	.08
October	.01	.11	.11	.20	.15	.12	.10
1978							
April	.02	.04	.03	.03	.02	.02	.02
June	.12	.12	.12	.15	.17	.18	.16
July	.17	.30	.32	.28	.25	<.01	.01
August	.06	.13	.16	.23	.17	<.01	<.01
November	.01	.06	.07	.12	.12	.13	.12

[1]See figure 1 for site locations.

Nitrate Nitrogen

The predominant form of nitrogen within the pond system is nitrate nitrogen (NO_3^-). At least 80 percent or more of the nitrogen in the water entering the pond system at site 2 is in the form of nitrate. Nitrate levels (table 7) were high compared to many standards and criteria for the water entering the pond system and remained high through Hager Pond and Grist Millpond. U.S. Environmental Protection Agency (1976) specifies 10 mg/L as the maximum allowable concentration of nitrate nitrogen for drinking-water supplies to provide protection for infants, who are susceptible to methemoglobinemia from ingestion of waters with high nitrate concentrations. Estimates of maximum nitrate concentrations that will not lead to nuisance growths of algae and other aquatic plants are variable. The U.S. Council on Environmental Quality (1975) assigned a maximum concentration of 0.6 mg/L of nitrate nitrogen as a "benchmark" level for aquatic life protection, suggesting that higher levels are indicative of undesirable eutrophication. Other criteria for nitrate nitrogen established by various States to limit eutrophication range from 0.10 mg/L in pristine waters to 3 mg/L in less-sensitive waters. A study of 365 sampling points on major rivers within the United States showed that nitrate nitrogen levels were below 1.0 mg/L at 85 percent of the sites and below 0.5 mg/L at 65 percent of the sites (Briggs and Ficke, 1978).

Table 7.—Concentrations of total nitrate nitrogen as N, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	18	—	15	—	—	—	7.6
1977							
April	5.7	4.0	5.4	3.7	2.1	1.3	2.3
June	21	13	14	9.9	9.9	5.6	4.8
August	16	9.5	9.7	5.4	4.7	.13	.27
October	16	11	9.9	8.8	8.2	5.4	4.9
1978							
April	6.8	4.8	2.8	2.5	2.3	1.8	1.7
June	18	9.7	9.4	5.6	5.5	2.0	1.8
July	14	5.1	5.3	1.8	1.7	.01	.10
August	4.2	6.1	5.8	1.1	1.0	.01	.14
November	18	16	16	14	14	7.8	7.5

[1]See figure 1 for site locations.

Nitrate nitrogen concentrations in the water entering the pond system were high in comparison to the criteria and examples given above. As explained earlier, the tributary entering Hager Pond at site 2 provided most of the water to the pond system, especially during the drier periods of the year. Even in wet periods, the tributary still accounted for half of the water flowing through the pond system. Because there was no other significant source of water to the system, the nitrate nitrogen concentrations, entering at site 2, were not diluted. Nitrate nitrogen concentrations did decrease as the water moved through the pond system; concentrations were as low as 0.01 mg/L by the time the water reached Carding Millpond.

Total Nitrogen

Total nitrogen (table 8) is the sum of organic nitrogen, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. Concentrations of nitrogen in the water leaving Carding Millpond were substantially lower than concentrations in Hager Pond or in the tributary entering Hager Pond. Table 9 shows loads of nitrogen, in pounds per day, entering Hager Pond, moving between ponds, and leaving Carding Millpond. The data in table 9 also show that for all sampling periods, there was net nitrogen removal from the pond waters when comparing site 2 with site 16. Figure 3 shows the amount removed during the study. A larger portion of the nitrogen was removed from the water during the summer months. Total nitrogen entering Hager Pond during the sampling periods of June, July, and August 1978 ranged from 153 to 594 pounds per day. Nitrogen leaving Carding Millpond during the same period ranged from 39 to 107 pounds per day.

Table 8.—Concentrations of total nitrogen as N, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	19	—	17	—	—	—	9.4
1977							
April	7.5	5.6	6.9	5.0	3.3	2.3	3.4
June	24	15	16	12	12	7.8	7.4
August	16	11	12	7.9	6.7	2.0	3.2
October	18	13	12	11	9.7	7.5	6.9
1978							
April	8.4	6.1	3.8	3.4	3.0	2.5	2.2
June	19	12	12	7.5	7.9	4.5	3.3
July	17	8.3	9.3	4.8	5.1	3.1	2.8
August	5.8	10	9.0	4.4	3.2	3.2	3.1
November	20	18	18	16	16	10	11

[1] See figure 1 for site locations.

Table 9.--Total nitrogen loads as N, in pounds per day, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	502	—	257	—	—	—	233
1977							
April	688	—	707	—	552	—	531
June	660	—	362	—	350	—	208
August	337	—	194	—	116	—	47
October	631	—	356	—	194	—	447
1978							
April	498	—	287	—	356	—	320
June	594	—	310	—	222	—	107
July	376	—	166	—	85	—	39
August	153	—	112	—	62	—	47
November	442	—	495	—	293	—	214

[1] See figure 1 for site locations.

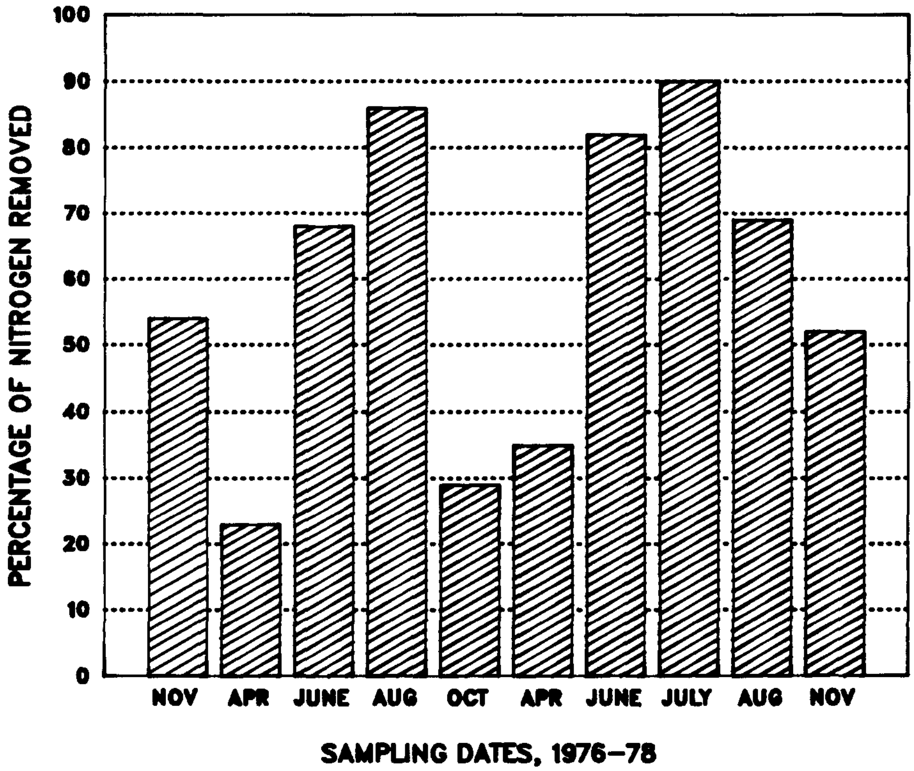

Figure 3.--Percentage of total nitrogen removed from the water column during transit through the ponds

Nitrogen is removed from the water column by two pathways—sedimentation and denitrification. Sedimentation occurs when organic material is incorporated into the bottom sediments. As the abundant algae and other aquatic plants die, their remains may sink to the bottom of the pond. If the material accumulates faster than it can be released, there will be a net loss of nitrogen into the bottom sediments. Nitrogen can be released back to the water column by a number of mechanisms, such as by decomposition of organic materials on the bottom, by rooted aquatic plants absorbing nutrients from the bottom sediments, and by disturbance of the bottom sediments by burrowing aquatic organisms.

Denitrification is the process by which nitrate is converted to elemental nitrogen gas. When the dissolved-oxygen concentration is zero or near zero, many bacteria are able to use nitrate as a source of oxygen to oxidize organic substances. Nitrate is converted to nitrogen gas which can be released to the atmosphere, thereby losing it from the system. The ponds in this study are particularly well adapted to denitrification. The ponds are shallow with an average depth of 5 feet or less. Jones and Simon (1981) found that the rate of denitrification and production of nitrogen gas was significantly faster in shallow water bodies (5 feet) compared to deep lakes. Dissolved-oxygen measurements in the pond indicated that the upper part of the water column had abundant oxygen during daylight hours. In the bottom 1 foot of the water column, the dissolved-oxygen concentration approached zero. Unlike deeper lakes, which will stratify during the summer with little mixing between the upper and the lower layers of water, the three ponds of this system are mixed by wind and wave action throughout the summer season. Fresh supplies of nitrate were available to the bottom sediments, and the bottom layer of water and could be used to oxidize the abundant organic material.

Rates of sedimentation and denitrification were not measured during the study; however, some estimate of the relative rates of the two can be made. Jones and Simon (1981) report that their literature review shows denitrification rates reported to be in the range of 0.8 to 6.0 millimoles per square meter per day (0.01 to 0.08 grams per square meter per day). The higher rates were in the more eutrophic water bodies. Applying the higher rate to the three ponds gives potential nitrogen removal rates of 19 pounds per day in Hager Pond, 9 pounds per day in Grist Millpond, and 23 pounds per day in Carding Millpond. Using the values shown in table 9, the average decrease in nitrogen load was 163 pounds per day in Hager Pond, 77 pounds per day in Grist Millpond, and 29 pounds per day in Carding Millpond. Comparison of the actual nitrogen removed from the water in the ponds and the calculated maximum nitrogen loss by denitrification, suggests that much of the nitrogen remains in the sediments of the ponds.

Phosphorus

Phosphorus data are reported as total phosphorus as P and total orthophosphate phosphorus as P. Total phosphorus includes all forms of phosphorus, such as soluble orthophosphate, soluble hydrolyzable phosphorus, soluble organic phosphorus, collodial material, and both inorganic and organic suspended materials. A large proportion of the phosphorus in the water column of a lake usually is bound organically as organic phosphates in the cellular material of the algae, vascular plants, and bacteria living in the water and sorbed or associated with inorganic and organic particulate matter. The previous discussion of nitrogen pointed out that there were several forms of inorganic nitrogen of importance to the aquatic plants of the pond system. Phosphorus, in contrast, has only one significant inorganic species, orthophosphate, which is readily available as a plant nutrient. Other species of phosphorus are in forms which are not available as nutrients to aquatic plants. These other species are important because they may be converted into orthophosphate and then may be available for plant growth.

Orthophosphate Phosphorus

Concentrations of orthophosphate phosphorus measured within the pond system are shown in table 10. Concentrations of orthophosphate phosphorus generally were highest at site 2 and decreased in Hager Pond and the other two ponds. Soluble orthophosphate is the form most available to the algae and bacteria as a nutrient source. Cycling of orthophosphate into particulate forms and then back to a soluble form can occur quickly. For example, orthophosphate can be taken up by algae, converted to organic phosphorus, and then excreted by the algae as a waste product. When algae die, their remains rapidly break down releasing soluble phosphate.

Table 10.—Concentrations of total orthophosphate phosphorus as P, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	0.21	—	0.17	—	—	—	0.16
1977							
April	.08	0.03	.07	0.05	0.03	0.02	.03
June	1.2	.16	.20	.11	.12	.13	.14
August	.80	.19	.20	.12	.11	.11	.24
October	.46	.14	.12	.09	.06	.06	.08
1978							
April	.14	.10	.05	.06	.05	.04	.04
June	.34	.26	.18	.21	.25	.23	.25
July	.10	.26	.22	.29	.25	.31	.27
August	.30	.28	.25	.14	.23	.31	.35
November	.42	.49	.38	.37	.31	.12	.12

[1]See figure 1 for site locations.

Total Phosphorus

Concentrations of total phosphorus within the pond system are shown in table 11. Total phosphorus is generally regarded as the measurement most critical in determining availability of phosphorus for algal and bacterial growth. U.S. Environmental Protection Agency (1976) discusses a proposed criterion designed to prevent or control nuisance aquatic-plant growth. This criterion proposes that total phosphorus levels not exceed 0.05 mg/L for any stream at the point where it enters a lake or reservoir or not exceed 0.025 mg/L within the lake or reservoir. USEPA uses the term "total phosphates" which is equivalent to the use by the Survey of the term "total phosphorus." The concentrations shown in table 11 are higher than the proposed criterion by an order of magnitude or more. Within the ponds, phosphorus was abundant at all sites. The total phosphorus concentrations were far in excess of the proposed criterion for prevention of nuisance aquatic-plant growth.

Table 11.—Concentrations of total phosphorus as P, in milligrams per liter, at the major sampling sites

Date	Site name and number[1]						
	Tributary to Hager Pond (2)	Hager Pond (5)	Hager Pond Outlet (8)	Grist Millpond (9)	Grist Millpond Outlet (12)	Carding Millpond (15)	Carding Millpond Outlet (16)
1976							
November	0.66	—	0.44	—	—	—	0.31
1977							
April	.34	0.22	.22	0.12	0.16	0.14	.16
June	3.0	.54	.51	.26	.23	.29	.33
August	2.1	.51	.44	.38	.26	.36	.54
October	1.7	.63	.46	.40	.26	.34	.33
1978							
April	.43	.29	.16	.16	.15	.10	.10
June	.58	.55	.48	.38	.45	.38	.36
July	.49	.47	.47	.54	.56	.53	.46
August	.76	.60	.34	.45	.34	.66	.60
November	.79	.70	.60	.45	.41	.24	.31

[1]See figure 1 for site locations.

Another way of expressing the amount of phosphorus which will cause undesirable aquatic growth within a lake is the annual phosphorus loading to the lake. Certain factors affect the amount of phosphorus loading that a lake may receive and yet still maintain a phosphorus level which will not cause excessive aquatic-plant growth. These factors include the surface area of the lake, the depth, and the amount of water entering the lake. From assessment of data on numerous lakes, R. A. Vollenweider developed the following equation (as expressed in Hammer and Mac Kichan, 1981):

$$P = \frac{L/q}{1+(z/q)^{0.5}} = \frac{Lt/z}{1+(t)^{0.5}} \tag{1}$$

where P = phosphorus concentrations in lake water, in grams per cubic meter
L = annual phosphorus loading, in grams per square meter per year
q = annual hydraulic loading, in meters per year, or mean depth/retention time (z/t)
z = mean depth, in meters
t = water renewal time (theoretical water-filling time), in years, or mean depth/hydraulic loading (z/q)

From the examination of data from a number of studies, the commonly accepted (Hammer and Mac Kichan, 1981) critical phosphorus concentration is 10 mg/m^3 (milligrams per cubic meter) or 0.01 mg/L at the end of the spring overturn. At this level or lower, lakes had no excessive algal growth during the growing season. Observed phosphorus levels greater than 20 mg/m^3 (0.02 mg/L) at the spring overturn produce eutrophic conditions. To determine what phosphorous loading is required to produce these phosphorous levels in a lake, equation 1 can be rearranged to:

$$L_c = P_c q \left[1 + \left(\frac{z}{q}\right)^{0.5}\right] = \frac{P_c z}{t}\left[1 + (t)^{0.5}\right] \tag{2}$$

where L_c = critical annual phosphorus loading, in grams per square meter
P_c = critical phosphorus concentrations at spring overturn, in grams per cubic meter
q = annual hydraulic loading, in meters per year
z = mean depth, in meters
t = water renewal time, in years

From equation 2, critical annual phosphorus loadings for the three ponds in this study may be calculated for the two levels of phosphorus concentrations. Results of these calculations for the 2 calendar years of the study are:

Site	Year	Observed annual phosphorus loading, in grams per square meter	Critical annual phosphorus loading, P_c = 10 mg/m^3, in grams per square meter	Critical annual phosphorus loading, P_c = 20 mg/m^3, in grams per square meter
Hager Pond	1977	115	0.71	1.42
	1978	34	.62	1.23
Grist Millpond	1977	53	1.37	2.74
	1978	45	1.19	2.38
Carding Millpond	1977	12	.57	1.14
	1978	17	.57	1.14