An investigation into the trophic status of Canyon Ferry Reservoir, Montana
by Ronald George Rada

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Botany
Montana State University

Abstract:
Canyon Ferry Reservoir is located on the Missouri River between Townsend and Helena, Montana. It initially reached maximum pool elevation during the summer of 1955. Wright studied the reservoir during 1956-1958 and documented its initial productivity level and trophic status. The present study, performed during 1971-1973, was undertaken to determine the extent and causes of any changes which occurred in Canyon Ferry during its initial 15-18 years of existence.

Canyon Ferry Reservoir could be characterized as a bicarbonate water with calcium as its most abundant cation. During the summer the Gallatin River contributed the majority of the nitrate observed in the initial reach of the Missouri River. Most of this nitrate was utilized in the Missouri River between the headwaters and Toston and did not reach the reservoir. There was a heavier load of inorganic nitrogen in the Missouri River at Townsend than at Toston while ortho-phosphorus loads were nearly equal at both locations. The increased inorganic nitrogen loads at Townsend were probably associated with irrigation return flows.

More inorganic nitrogen was observed in the outflow as compared to the inflow of Canyon Ferry Reservoir. The most logical explanation is nitrogen fixation by the blue-green alga, Aphanizomenon flos-aquae, during the summer. The extent of spring drawdown of the reservoir appeared to be a significant factor in the amount of nitrogen recycled to the reservoir each year. Loads of total phosphorus were nearly equal in the inflow and outflow while much of the combined phosphorus that entered the reservoir was converted to ortho-phosphorus which was discharged. Canyon Ferry's deep-water withdrawal allowed it to discharge large loads of inorganic nitrogen and phosphorus which helped alleviate many of the problems associated with high specific surface loading of nutrients.

The phytoplankton in Canyon Ferry consisted of 65 species and was primarily a blue-green algae/diatom flora. Aphanizomenon flos-aquae had the largest standing crops while Fragilaria crotonensis, Stephanodiscus niagarae, Melosira granulata, and Diatoma elongatum were also prominent. The diatoms sustained relatively larger standing crops during 1971 when the levels of inorganic nitrogen were higher than in 1972. A. flos-aquae attained bloom proportions during the summer when the surface temperature approached 20°C and the euphotic zone nitrate concentrations became undetectable. Nitrate appeared to be more limiting than ortho-phosphorus; however, the blue-greens compensated for this by nitrogen fixation.

Canyon Ferry could be classified as a moderately productive or slightly eutrophic reservoir. There was no evidence to indicate that the reservoir had become more eutrophic from 1957-1958 to 1971-1972. In fact, it appeared to have become less eutrophic. Canyon Ferry Reservoir lost its high initial level of productivity and appeared to be approaching a lower steady state level of production by 1971-1972. This level of production should continue throughout much of the life of the reservoir.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

Page

ABSTRACT

Canyon Ferry Reservoir is located on the Missouri River between Townsend and Helena, Montana. It initially reached maximum pool elevation during the summer of 1955. Wright studied the reservoir during 1956-1958 and documented its initial productivity level and trophic status. The present study, performed during 1971-1973, was undertaken to determine the extent and causes of any changes which occurred in Canyon Ferry during its initial 15-18 years of existence.

Canyon Ferry Reservoir could be characterized as a bicarbonate water with calcium as its most abundant cation. During the summer the Gallatin River contributed the majority of the nitrate observed in the initial reach of the Missouri River. Most of this nitrate was utilized in the Missouri River between the headwaters and Toston and did not reach the reservoir. There was a heavier load of inorganic nitrogen in the Missouri River at Townsend than at Toston while ortho-phosphorus loads were nearly equal at both locations. The increased inorganic nitrogen loads at Townsend were probably associated with irrigation return flows.

More inorganic nitrogen was observed in the outflow as compared to the inflow of Canyon Ferry Reservoir. The most logical explanation is nitrogen fixation by the blue-green alga, *Aphanizomenon flos-aquae*, during the summer. The extent of spring drawdown of the reservoir appeared to be a significant factor in the amount of nitrogen recycled to the reservoir each year. Loads of total phosphorus were nearly equal in the inflow and outflow while much of the combined phosphorus that entered the reservoir was converted to ortho-phosphorus which was discharged. Canyon Ferry's deep-water withdrawal allowed it to discharge large loads of inorganic nitrogen and phosphorus which helped alleviate many of the problems associated with high specific surface loading of nutrients.

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Canyon Ferry could be classified as a moderately productive or slightly eutrophic reservoir. There was no evidence to indicate that the reservoir had become more eutrophic from 1957-1958 to 1971-1972. In fact, it appeared to have become less eutrophic. Canyon Ferry Reservoir lost its high initial level of productivity and appeared to be approaching a lower steady state level of production by 1971-1972. This level of production should continue throughout much of the life of the reservoir.

INTRODUCTION

Canyon Ferry is a reservoir on the Missouri River between Townsend and Helena, Montana. Its main uses are power production, flood control, irrigation, recreation, and municipal water supply. Since its origin, it has become increasingly popular as a recreational site. Canyon Ferry initially reached maximum pool elevation during the summer of 1955. Wright (1958, 1959, 1960, 1961, 1965, and unpublished data) studied the reservoir during 1956-1958. His study documented the initial productivity level and trophic status of Canyon Ferry and therefore offered baseline data for the newly impounded reservoir. Later it became of interest to determine the changes which occurred in the reservoir since its origin. The present study, performed during 1971-1973, was undertaken to establish the extent and causes of any changes in Canyon Ferry during its initial 15-18 years of existence. In order to gain a comprehensive understanding of the factors affecting Canyon Ferry, the study included the entire reservoir, the Missouri River, and its headwater streams. The main objectives of the present study were as follows:

(1) To determine the hydrologic regime and its effects on the limnological status of the reservoir.

(2) To determine the nutrient loads (mainly nitrogen and phosphorus) of the Missouri River headwater streams.

(3) To determine the nutrient loads of the Missouri River at Toston and Townsend to assess the input from agricultural irrigation return flows.

(4) To determine the storage of nutrients within the reservoir and the factors which affect them.

(5) To characterize the general type of water in the reservoir and its tributaries with respect to cations and anions.

(6) To compute a nutrient budget for the reservoir and determine the factors which affect it.

(7) To determine phytoplankton standing crops and primary production and the factors which affect them.

DESCRIPTION OF THE STUDY AREA

Canyon Ferry Reservoir is formed from impoundment of the Missouri River by Canyon Ferry Dam which is located at lat. 46°38'57", long. 111°43'39", in SE 1/4 SE 1/4 Sec. 4, T. 10 N., R. 1W, in Lewis and Clark County approximately 24 km (15 mi) east of Helena, Montana. Contents of the reservoir are used for power production, flood control, irrigation, recreation, and supplemental water supply for the city of Helena.

The reservoir is formed by a concrete dam, built and operated by the United States Bureau of Reclamation. The dam has a crest length of 304.8 m, top width of 6.1 m, and a maximum base width of 52.7 m. Construction was initiated in 1949 and water storage began in April, 1953. Storage at the top of joint use elevation (1,157.3 m) is 2.401.4 x 10^6 m^3 while storage at the minimum operating level for power generation is 536.1 x 10^6 m^3. Surface area of the reservoir at the top of the joint use elevation is 13,936 ha (34,435 acres). Area and capacity data for Canyon Ferry Reservoir are shown in Table 1.

At maximum pool elevation (1,158.2 m), the length of Canyon Ferry Reservoir is 40.2 km (25 mi) and the maximum breadth is 7.2 km (4.5 mi). Average depth of the reservoir is 17.8 m (58.4 ft); however, it reaches a maximum depth of 50.1 m (164.5 ft) directly upstream from the dam. Morphometric data for Canyon Ferry Reservoir are presented in Table 2.

The Missouri River is formed by the confluence of the Gallatin, Madison, and Jefferson rivers near Three Forks, Montana. Its total drainage area to Canyon Ferry Dam is 41,191 km^2 (15,904 mi^2).

Table 1. Surface area and capacity of Canyon Ferry Reservoir at specified operating levels.

	Elevation meters (feet)	Surface Area ha (acres)	Capacity x 10^6 m^3 (acre-feet)
Crest of dam	1,160.8 (3,808.5)	--	--
Maximum water surface	1,158.2 (3,800)	14,238 (35,181)	2,530.0 (2,050,900)
Top of exclusive flood control	1,158.2 (3,800)	14,238 (35,181)	2,530.0 (2,050,900)
Bottom of exclusive flood control	1,157.3 (3,797)	13,936 (34,435)	2,401.4 (1,946,624)
Top of joint use	1,157.3 (3,797)	13,936 (34,435)	2,401.4 (1,946,624)
Bottom of joint use	1,157.3 (3,797)	9,764 (24,126)	1,415.6 (1,147,500)
Top of active conservation	1,149.1 (3,770)	9,764 (24,126)	1,415.6 (1,147,500)
Top of inactive storage	1,136.3 (3,728)	4,646 (11,479)	536.1 (434,537)
Top of dead storage	1,112.5 (3,650)	405 (1,000)	9.9 (8,000)
Stream bed at dam axis	1,108.1 (3,635.5)	0	0

Table 2. Morphometric data for Canyon Ferry Reservoir at maximum pool elevation (1,158.2 m).

Maximum depth	50.1 m (164.5 ft)
Mean depth*	17.8 m (58.4 ft)
Maximum length	40.2 km (25 mi)
Maximum breadth	7.2 km (4.5 mi)
Mean breadth*	3.5 km (2.2 mi)
Surface area	14,238 ha (35,181 acres)
Volume	2,530 x 10^6 m^3 (2,050,900 acre-ft)
Length of shoreline	122.3 km (76 mi)
Shoreline development*	2.89
Slope of basin	0.12%

*Definition and discussion of these parameters can be obtained from Reid (1961).

The Gallatin River at Logan, Montana, drains 4,649 km^2 (1,795 mi^2) and is formed by the confluence of the West Gallatin River which originates in northwest Yellowstone National Park and the East Gallatin River which originates north of Bozeman, Montana.

Confluence of the Firehole and Gibbon rivers in the midwest region of Yellowstone National Park forms the Madison River. At McAllister, Montana, the Madison drainage area is 5,662 km^2 (2,186 mi^2).

The Bighole, Beaverhead, and Ruby rivers combine to form the Jefferson River which has a drainage area at Sappington, Montana, of 19,767 km^2 (7,632 mi^2).

A general geological description of the study area can be found in Alt and Hyndman (1972).

Eight permanent stations were established for use during the "regular" sampling season (mid-May through mid-September). Four of these stations were within the reservoir and were located near the dam and at approximately 8-km (5-mi) intervals upstream (Figure 1). These stations will be referred to as Station 1 (km 0, in the vicinity of the dam), Station 2, Station 3, and Station 4 (approximately 24 km or 15 mi upstream from Canyon Ferry Dam). There were two permanent stations located on the Missouri River above Canyon Ferry at Toston and Townsend. The remaining two permanent stations were located in the Helena Valley irrigation canal and in the Missouri River directly below the Canyon Ferry discharge.

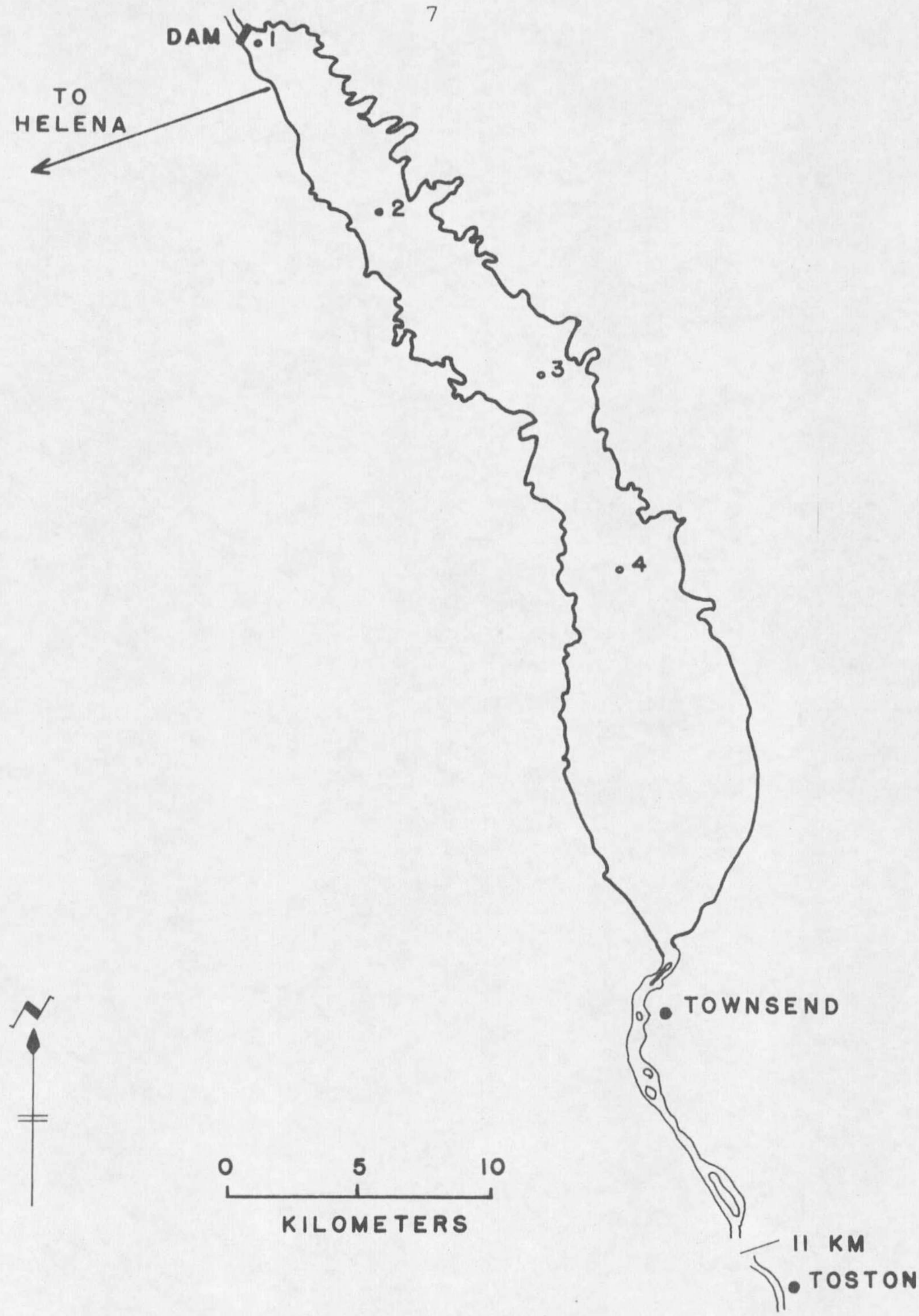

Figure 1. A map of the study area. The locations of sampling stations within the reservoir are indicated by the numbers 1-4.

The Toston, Townsend, and discharge stations were monitored during October, 1972 to April, 1973, in addition to during the regular sampling season. During 7 July to 7 September 1971, the Jefferson, Madison, and Gallatin rivers were sampled at locations above their confluence.

METHODS AND MATERIALS

Inflow and Outflow Waters

Water samples were taken at weekly intervals from all previously described Missouri River stations during the 15 May - 18 September 1971 and 13 May - 18 September 1972 periods. In addition, samples were taken at monthly intervals from October, 1972 through April, 1973.

As a supplement to this study, Roger Schelin (Botany and Microbiology graduate student) sampled the Gallatin, Madison, and Jefferson rivers at weekly intervals from 7 July 1971 through 7 September 1971.

All samples were obtained by lowering an 8-liter polyethylene bucket into the main current of the river. The bucket was rinsed with river water before collecting the sample water. A 1-liter polyethylene bottle and a 300-ml glass-stoppered Pyrex bottle were filled with water from each river station. All sample bottles were rinsed with deionized distilled water in the laboratory and with river water prior to taking the sample.

Temperature and Conductivity

The temperature of the water sample was taken upon collection with an E. H. Sargent & Co. -10 to 100°C mercury thermometer.

The electrical resistance of the water sample was measured at a frequency of 1 kHz with a Yellow Springs Instrument Co. AC conductivity bridge (Model 31) equipped with an Industrial Instruments Co. dipping cell (Model CEL-S2). Specific conductance is reported as $\mu mhos \cdot cm^{-1}$ at 25°C.

Water Chemistry

Sample preparation. At the laboratory the water in the 300-ml glass bottles was filtered through Millipore® membrane filters with a pore size of 0.45 microns. This water was used for the nutrient analyses, i.e. phosphorus species, nitrate, nitrite, and ammonia. In addition, approximately 500 ml of the water in the 1-liter polyethylene bottle was filtered and used for analyses of total hardness, calcium hardness, sodium, potassium, sulfate, fluoride, and chloride.

pH. The hydrogen ion concentration was determined in the field at the time of collection with Orion portable pH meters (Models 401 and 407) as well as in the laboratory during the alkalinity analysis.

Phosphorus. Total phosphorus and soluble inorganic phosphorus were determined using the Single Reagent Method described by the Environmental Protection Agency (1971). Combined phosphorus was then computed as the difference between total and ortho-phosphorus. Total phosphorus included particulate, dissolved organic phosphorus, and dissolved inorganic phosphorus (ortho-phosphorus). Combined phosphorus included particulate and dissolved organic phosphorus. Phosphorus concentrations are reported as $\mu g \cdot P \cdot L^{-1}$.

Nitrogen. The method of Mullin and Riley as described by Barnes (1959) was used in the analysis of nitrate. Nitrite was determined using Hach Chemical Company's NitriVer® reagent. Nitrate and nitrite loads and storage were computed together and collectively reported as kg NO_3^--N. In all other cases, nitrate and nitrite were computed separately and reported as $\mu g\ NO_3^- \text{-N} \cdot L^{-1}$ and $\mu g\ NO_2^- \text{-N} \cdot L^{-1}$. The phenolhypochlorite method of Solorzano (1969) was used for the ammonia analysis. Ammonia concentrations are reported as $\mu g\ NH_3 \text{-N} \cdot L^{-1}$.

Major cations. Measurement of sodium and potassium concentrations was made using flame emission spectrophotometry with a Beckman DU Flame Spectrophotometer according to procedures given in the Beckman Instruction Manual 334-A and APHA (1971).

Total hardness and calcium hardness were determined by complexometric methods using Hach Chemical Company's Standard HexaVer^R as the titrant and ManVer^R and CalVer^R, respectively, as the indicators. Magnesium hardness was computed as the difference between total hardness and calcium hardness.

Major anions. Hach Chemical Company's SulfaVer^R III and a series of sulfate standards were used to measure sulfate concentrations.

Chloride was determined by the Mercuric Nitrate Method (APHA 1971) utilizing Hach Chemical Company's standard 0.0141 N mercuric nitrate as the titrant and diphenylcarbazone indicator-buffer.

Fluoride was determined by the SPADNS Method (APHA 1971) utilizing Hach Chemical Company's acid zirconyl-SPADNS reagent.

Total alkalinity analysis was performed on an unfiltered sample by a potentiometric titration method (APHA 1971) with 0.1 N standard sulfuric acid as the titrant.

All the above mentioned chemical analyses were performed on each sampling date except sodium, potassium, chloride, fluoride, and sulfate which were performed at monthly intervals.

Tests for total phosphorus, combined phosphorus, ortho-phosphorus, nitrate, nitrite, ammonia, conductivity, total alkalinity, and pH were performed within 18 hours after collection. Total hardness, calcium hardness, fluoride, chloride, and sulfate were analyzed within 36 hours after collection. Sodium and potassium were determined within 96 hours after collection.

Turbidity

The turbidity of each weekly sample was determined using a Hach Laboratory Turbidimeter (Model 2100) and reported as Standard Jackson Turbidity Units.

Reservoir

All samples and in situ measurements were taken at weekly intervals during the periods of 15 May - 18 September 1971 and 13 May - 18 September 1972.

Light

A vertical profile of light extinction was obtained through the euphotic zone of the water column at each station on each sampling date. The profile was obtained by recording with a Gemware Photometer (selenium photocell) the in situ total visible light intensity at the water surface and at 1-m intervals until a depth at which an intensity of only 1% of the surface light intensity was obtained.

The depth at which photosynthesis is balanced by respiration so that there is no net photosynthetic increase in organic matter is the compensation depth (Edmondson 1956). The depth to which only 1% of the incident radiation penetrates sets the lower limit of the euphotic zone since this is the depth of the compensation point (Verduin 1964 and Ryther 1956a).

The mean vertical extinction coefficients (Hutchinson 1957) were determined for the euphotic zone of each station on each date as a measure of transparency.

Temperature

A vertical profile of temperature was obtained using a Wallace and Tiernan bathythermograph (Model FA.190012). Carbon-plated slides were used in 1971 and Kahl Scientific Instrument Corporation gold-plated slides in 1972.

Water Chemistry

All water samples were taken with a 3-liter Van Dorn bottle. Samples were collected at 5-m intervals from the surface to the bottom of the reservoir at each station. Chemical analyses on these samples included total phosphorus, combined phosphorus, ortho-phosphorus, nitrate, nitrite, ammonia, sodium, potassium, total hardness, calcium hardness, sulfate, chloride, fluoride, total alkalinity, and pH. These tests were conducted using the same methods and procedures previously described.

In addition, samples were taken at 1-m intervals from the surface through the euphotic zone. The samples were then mixed to form a euphotic zone composite sample that was used for the above chemical analyses plus chlorophyll determination and phytoplankton enumeration.

Phytoplankton Standing Crop and Chlorophyll *a*

An aliquot of the euphotic zone composite sample for phytoplankton enumeration was immediately treated with Lugol's solution containing acetic acid. The iodine in Lugol's solution has staining properties as well as being a preservative in low concentrations and the acetic acid preserves cilia and flagella. When a sample is treated with Lugol's solution and is kept tightly closed in the dark, it will keep for years (Schwoerbel 1970).

Later in the laboratory, the Lugol's-treated phytoplankton samples were shaken until the phytoplankton were homogeneously distributed. Subsamples were then withdrawn and prepared for microscopic analyses according to the Membrane Filter Concentration Technique (APHA 1971). The subsamples ranged in volume from 3 to 50 ml depending upon the concentration of phytoplankton in the sample. The phytoplankton were identified and counted in transects along the diameter of the filter. At least three transects were counted, i.e. one transect at each of three magnifications: 100X, 430X, and 970X. In addition to identification and enumeration of phytoplankton, the organisms were measured with a Whipple ocular micrometer and the cell volume of each counted organism was calculated. For example, if the organism was shaped like a sphere, cylinder, cone, oblate spheroid, etc., the appropriate geometric formula was used to calculate the volume of that particular geometric object.

All phytoplankton standing crop data are reported as cell volume of each type of organism per liter ($mm^3 \cdot L^{-1}$). Cell volume was determined since phytoplankton organisms differ greatly in size; hence, number per liter does not give a true picture of the actual biomass (Findenegg 1969). Lund et al. (1958) discussed the statistical significance of using direct count methods for estimation of populations. During the study, at least 100 organisms were counted from each sample; therefore, the 95% confidence limits for the counts were 100 ± 20 (Lund et al. 1958). Moore (1952) also discussed the precision of microscopic counts of plankton in water.

The phytoplankton were identified to the species level in most instances; however in some cases, identification to only the generic level could be attained. The taxonomic keys used for the identification of phytoplankton organisms are by Smith (1950), Prescott (1962), Drouet (1959), Hustedt (1930), FWPCA (1966), and Taft and Taft (1971).

The group reported as "microplankton" included small green algae, e.g. *Chlamydomonas*, *Carteria*, *Chlorella*, etc. which were too badly distorted by the treatment process to allow absolute identification.

Chlorophyll *a* concentrations were determined by filtering a known volume of euphotic zone composite water (usually 500 ml) through a Millipore^R membrane filter (0.45 μ diameter pore size). The filters were then placed in 15-ml stoppered centrifuge tubes to which 5 ml of 90% acetone was added. The chlorophyll was extracted by placing the tubes in complete darkness in a refrigerator for 24 hours. The tubes were then centrifuged and the extinction of the supernatant was measured with a Beckman DU Spectrophotometer using a 1-cm path length according to the method of Strictland and Parsons (1968). The chlorophyll *a* concentration ($\mu g \cdot L^{-1}$) was then computed using the equations of Strictland and Parsons (1968).

Primary Production

Ryther and Yentsch (1957) presented an equation for estimating primary production using chlorophyll and light data. Their equation was written:

$$P = \frac{R}{k} \times C \times 3.7 \qquad (1)$$

where P was photosynthesis of the phytoplankton population in $g\ C \cdot m^{-2} \cdot day^{-1}$, R was the relative photosynthesis for the appropriate value of surface radiation (Ryther 1956a), k was the average extinction coefficient$\cdot m^{-1}$, C was g chlorophyll $a \cdot m^{-3}$ in a sample from a homogeneously distributed population, and 3.7 was an average assimilation ratio at light saturation.

Martin (1967) showed that the assimilation ratio at light saturation was independent of the amount of sunlight falling on the lake surface. He further demonstrated a linear relationship when the log of the assimilation ratio at light saturation was plotted against average temperature of the euphotic zone. Martin (1967) subsequently modified the original equation (1) of Ryther and Yentsch (1957) to the following:

$$P = \frac{R}{k} \times C \times A_T \qquad (2)$$

where P, R, and k were the same as equation (1) and A_T was the temperature dependent assimilation ratio.

Ryther and Yentsch (1957) acknowledged that the chlorophyll-photosynthesis factor was the weakest point in the model. They also stated that the use of accurate, narrow-band spectrophotometers could reduce the errors. Manning and Juday (1941) and Wright (1959) found a highly significant relationship between optimal photosynthesis and chlorophyll concentration. Brylinsky and Mann (1973) and Tunzi and Porcella (1974) further demonstrated that the rate of carbon assimilated was highly correlated with chlorophyll. Therefore, if the more accurate light-dark bottle oxygen or carbon-14 methods are not practical for use in a particular study, the estimation of net primary productivity from chlorophyll and solar radiation data should be a reasonable alternative. A detailed comparison of the various methods of estimating primary production can be found in Saunders et al. (1962).

Martin's (1967) equation utilizing solar radiation data from Kimball (1928) was used to estimate primary production during this study.

The photosynthetic quotient can vary with the composition of algae and with environmental conditions, e.g. the nitrogen source. Ryther (1956b) and Strictland (1960) suggested photosynthetic quotients of 1.25 and 1.2, respectively, for routine measurements of natural populations. A photosynthetic quotient of 1.2 was chosen in this study to convert g $C \cdot m^{-2} \cdot day^{-1}$ to g $O_2 \cdot m^{-2} \cdot day^{-1}$.

RESULTS AND DISCUSSION

Hydrology

Hydrologic data were supplied by the U.S. Geological Survey (1971 and 1972) and the U.S. Bureau of Reclamation (1971-1973 unpublished data).

The only significant inflow of water into Canyon Ferry was the Missouri River at the extreme upper end of the reservoir. All outflow was discharged through the dam; however, the discharge water was drawn from several different elevations; i.e., 1,157 m (spillway), 1,130 m (power penstocks), 1,125 m (Helena Valley irrigation), and 1,114 m (river outlets).

The penstocks were the only method of discharge used during October to March and accounted for 47-95% of the discharge throughout the remainder of the year. Irrigation water for the Helena Valley was withdrawn during April to September each year and comprised 2-12% of the discharge during these months. Only at times of peak runoff (late June and early July) was the spillway used to discharge water. The river outlets, which were in operation from April to July, 1971, and April to June, 1972, accounted for 14-48% of the discharge throughout these months. Discharge data for Canyon Ferry Dam are given in Table 3.

Spring runoff, due largely to snow melt of the mountainous Gallatin, Madison, and Jefferson river drainages, began in April each year. The runoff accounted for the higher inflows into the reservoir during this time. Inflows increased from April through late June, 1971, and from

Table 3. Average relative amounts of discharge water (% of total discharge) passing through the respective outlets of Canyon Ferry Dam during the calendar years 1971 and 1972.

	Month	Penstocks	River Outlet	Irrigation Intake	Spillway
	January	100	--	--	--
	February	100	--	--	--
	March	100	--	--	--
	April	68	29	3	--
1	May	47	48	4	--
9	June	70	18	7	5
7	July	57	14	7	22
1	August	88	--	12	--
	September	95	--	5	--
	October	100	--	--	--
	November	100	--	--	--
	December	100	--	--	--
	January	100	--	--	--
	February	100	--	--	--
	March	100	--	--	--
	April	69	29	2	--
1	May	61	34	5	--
9	June	58	17	7	18
7	July	82	--	10	8
2	August	91	--	9	--
	September	94	--	6	--
	October	100	--	--	--
	November	100	--	--	--
	December	100	--	--	--

April through mid-June, 1972. Reservoir drawdown, in preparation for runoff, was apparent from the large outflows which occurred during May of both years (Figure 2).

During each calendar year, Canyon Ferry Reservoir was steadily drawn down to the year's lowest surface elevations in May. In 1971 the minimum water elevation was 1,150.9 m on 28 May and the maximum elevation was 1,157.5 m on 2 July. Accompanying the change in surface elevation was a change in surface area of the reservoir. This means that in 1971 an area of 3,013 ha (7,445 acres) of reservoir bottom was exposed to the atmosphere at maximum drawdown. In 1972 the minimum level of the reservoir during drawdown was 1,152.7 m on 17 May while the maximum level was 1,157.4 m on 27 June, exposing an additional 2,152 ha (5,316 acres) at minimum level.

After the highest water level in July, 1971, the lake surface was steadily lowered through August and then remained relatively constant for the rest of the year. Subsequent to the highest surface elevations in 1972, the trend was a lowering of the surface levels during the remainder of the year. Figure 3 and Table 4 show the trends of reservoir surface elevations and areas. The difference in the hydrologic regime between 1971 and 1972, especially during spring drawdown, appeared to have a significant effect on the nitrogen cycle in 1971 as compared to 1972. This will be discussed in a later section on the nitrogen interactions within the reservoir.

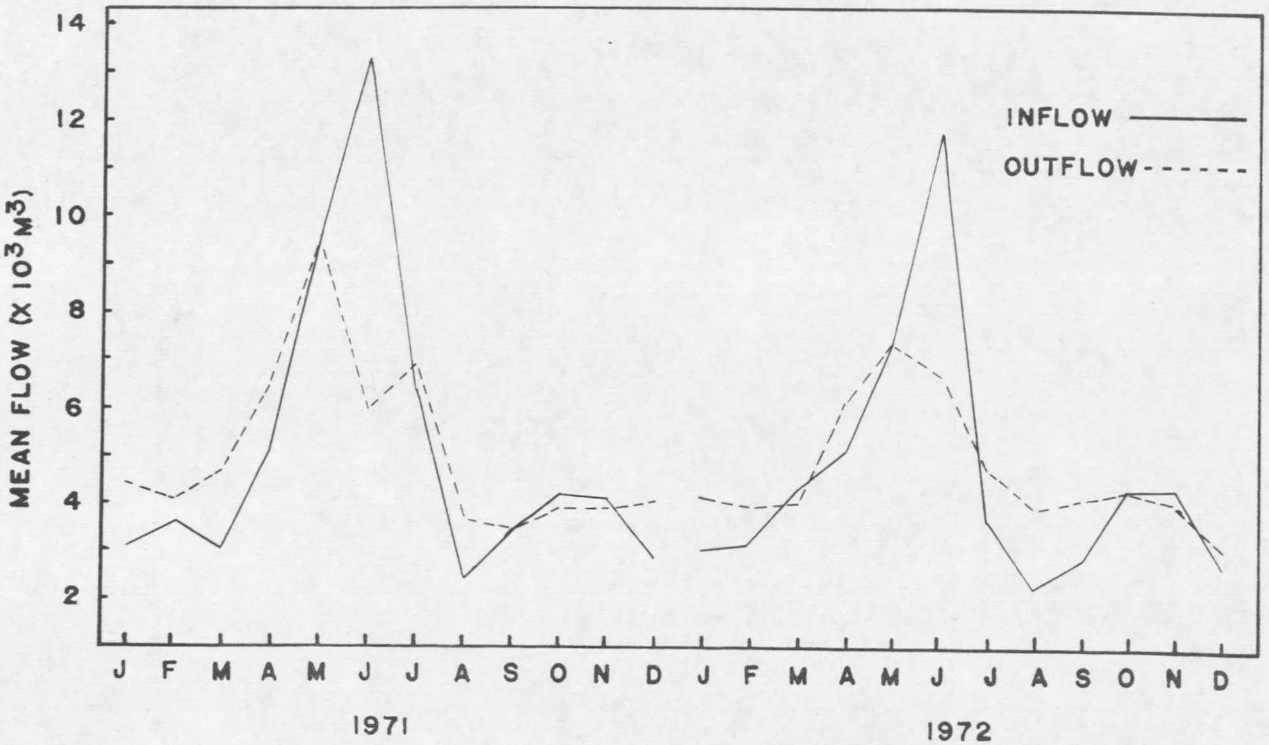

Figure 2. Average monthly rates of inflow to and outflow from Canyon Ferry Reservoir during the 1971 and 1972 calendar years.

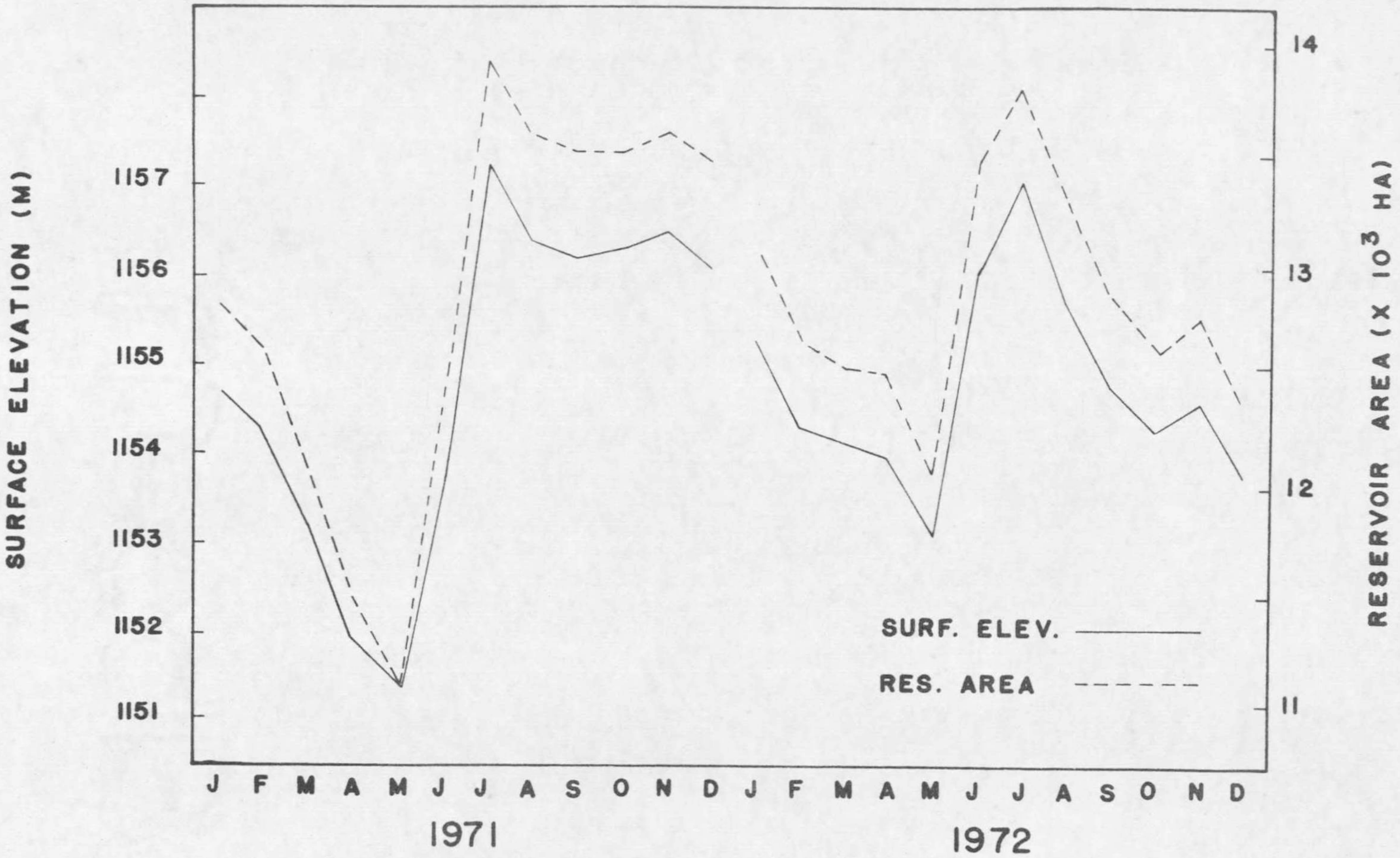

Figure 3. Average monthly reservoir surface elevations and surface areas during the 1971 and 1972 calendar years.

Table 4. Summary of hydrological data for Canyon Ferry Reservoir during the calendar years 1971 and 1972.

		Total Inflow x $10^6 m^3$	Total Outflow x $10^6 m^3$	Storage Change x $10^6 m^3$	Average Storage x $10^6 m^3$	Average Discharge x $10^6 m^3$ day^{-1}	Retention Time days	Average Surface Elevation (m)	Average Surface Area (ha)
	Jan.	317.0	447.8	-130.8	2,045.9	14.4	142.1	1,154.7	12,816
	Feb.	370.4	414.3	- 43.9	1,992.2	14.8	134.6	1,154.2	12,608
	Mar.	310.0	474.4	-164.4	1,870.2	15.3	122.2	1,153.2	12,094
	Apr.	513.4	647.1	-133.7	1,715.5	21.6	79.4	1,151.9	11,484
	May	979.3	960.0	+ 19.3	1,653.1	31.0	53.3	1,151.4	11,069
1	June	1,332.6	604.4	+728.2	2,035.9	20.1	101.3	1,153.7	12,317
9	July	642.3	687.1	- 44.8	2,394.3	22.2	107.9	1,157.3	13,925
7	Aug.	253.8	380.2	-126.4	2,281.2	12.3	185.5	1,156.4	13,600
1	Sept.	358.9	353.2	+ 5.7	2,250.4	11.8	190.7	1,156.2	13,512
	Oct.	427.8	399.1	+ 28.7	2,254.3	12.9	174.8	1,156.3	13,525
	Nov.	423.0	397.3	+ 25.7	2,282.7	13.2	172.9	1,156.5	13,612
	Dec.	294.2	414.3	-120.1	2,235.9	13.4	166.9	1,156.1	13,462
	Ave.				2,084.3		136.0		
	Total	6,222.7	6,179.2	+ 43.5					
	Jan.	311.0	424.9	-113.9	2,123.8	13.7	155.0	1,155.3	13,087
	Feb.	324.2	408.0	- 83.8	2,003.8	14.1	142.1	1,154.3	12,653
	Mar.	438.7	413.9	+ 24.8	1,978.9	13.4	147.7	1,154.1	12,548
	Apr.	521.4	621.6	-100.2	1,963.6	20.7	94.9	1,154.0	12,487
	May	744.9	747.5	- 2.6	1,859.6	24.1	77.2	1,153.1	12,046
1	June	1,186.9	681.3	+505.6	2,244.4	22.7	98.9	1,156.1	13,474
9	July	372.8	483.0	-110.2	2,361.6	15.6	151.4	1,157.1	13,826
7	Aug.	230.2	395.5	-165.3	2,181.6	12.8	170.4	1,155.7	13,292
2	Sept.	293.4	416.7	-123.3	2,060.1	13.9	148.2	1,154.8	12,860
	Oct.	439.0	436.3	+ 2.7	1,995.6	14.1	141.5	1,154.3	12,623
	Nov.	445.2	415.1	+ 30.1	2,034.0	13.8	147.4	1,154.6	12,772
	Dec.	279.7	408.8	-129.1	1,939.0	13.2	146.9	1,153.8	12,394
	Ave.				2,062.2		135.1		
	Total	5,587.5	5,852.7	-265.2					

The average annual water volume was 2,084.3 x 10^6 m^3 in 1971 as compared to 2,062.2 x 10^6 m^3 in 1972. An annual change in storage of +43.5 x 10^6 m^3 occurred in 1971 while a net storage change of -265.2 x 10^6 m^3 occurred in 1972. The negative value in 1972 was because of less drawdown in 1972 than in 1971. In other words, with less drawdown there was less volume in the reservoir for net storage (Table 4).

The average water retention times were 136 days in 1971 and 135 days in 1972. Retention times were shortest during May each year, which reflected drawdown in preparation for runoff, and were longest during the summer when maximum surface elevations were attained (Table 4).

Inflow and Outflow Waters

Turbidity

Turbidity in the Missouri River directly above Canyon Ferry Reservoir ranged from 1.9-105 JTU in 1971 and 3.0-44 JTU in 1972. The maximum turbidity was observed during June each year when runoff was greatest. A significant correlation ($r = 0.91$, $p < 0.01$) existed between flow and turbidity which suggests that the higher turbidity in 1971 could be attributed to the higher maximum flow observed during that year.

During the period of spring runoff when turbidity was high, the relative concentrations of total and ortho-phosphorus were substantially higher than at times of normal flow. The correlation coefficient for ortho-phosphorus versus turbidity was $r = 0.63$ ($p < 0.01$). A similar type of relationship was noted by Wright and Soltero (1973) and was partially attributed to base exchange equilibria between the water and suspended sediments with a subsequent release of ortho-phosphorus from the sediments. Effects of suspended material on the phosphorus concentration in solution are discussed by Biggar and Corey (1969).

While the turbidity in the inflow reached relatively high concentrations during the spring, the outflow turbidity never exceeded 7.4 JTU during the study period. Figure 4 depicts the average turbidity at various locations within the study area. It will be shown in a later section that most of the turbidity that entered Canyon Ferry settled out in the upper 16 km (10 mi) of the reservoir.

Temperature

The temperature of the inflow was substantially higher than the outflow during most of the regular sampling period (Figure 5).

Inflow temperature increased from a minimum in May to a maximum in August. During September the inflow temperature dropped to near or below the temperature of the outflow.

The outflow behaved in a somewhat different manner than the inflow in regard to temperature. The most notable difference between inflow and outflow temperature patterns was a more gradual rise in the latter. Differences in the thermal regime of the outflow compared to the inflow

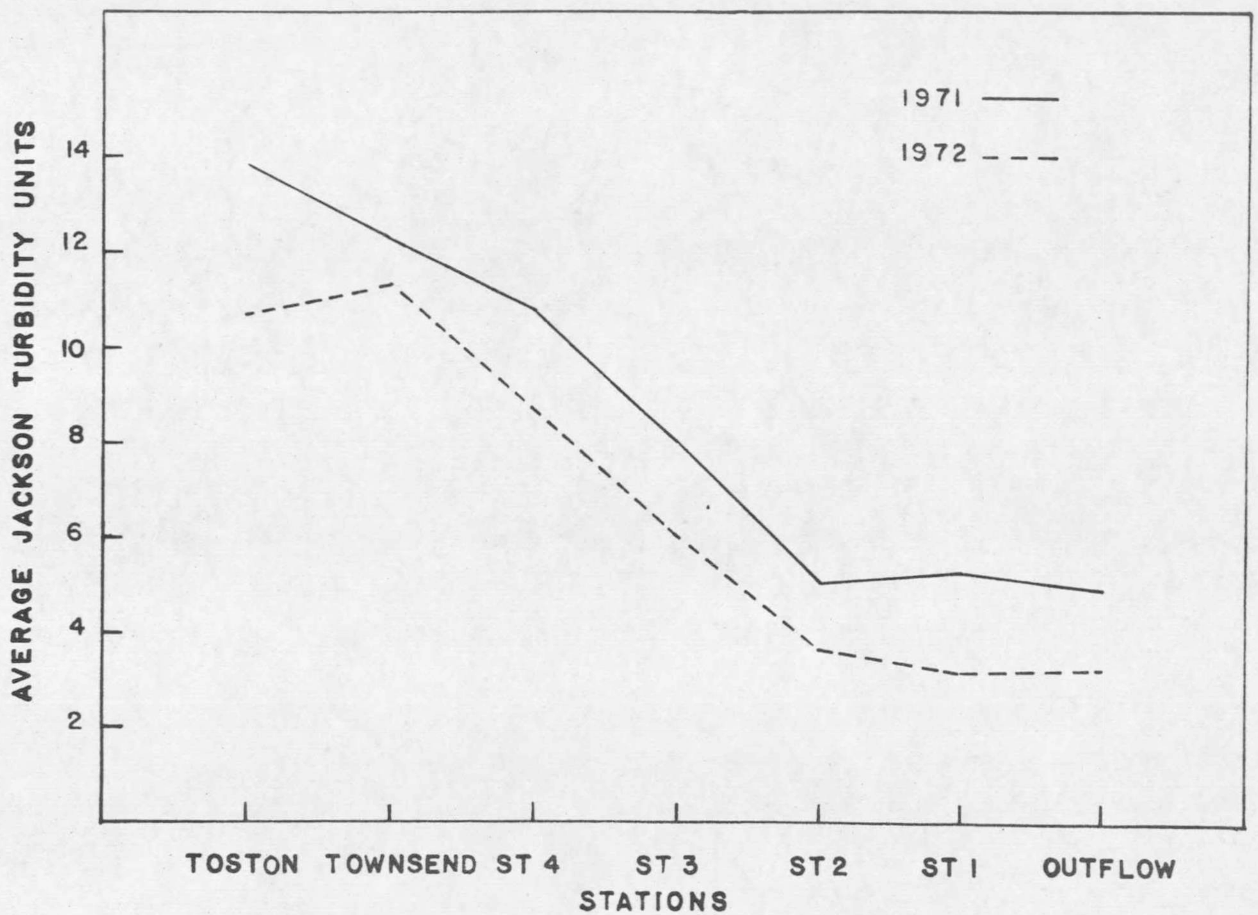

Figure 4. Average turbidity at various locations within the study area.

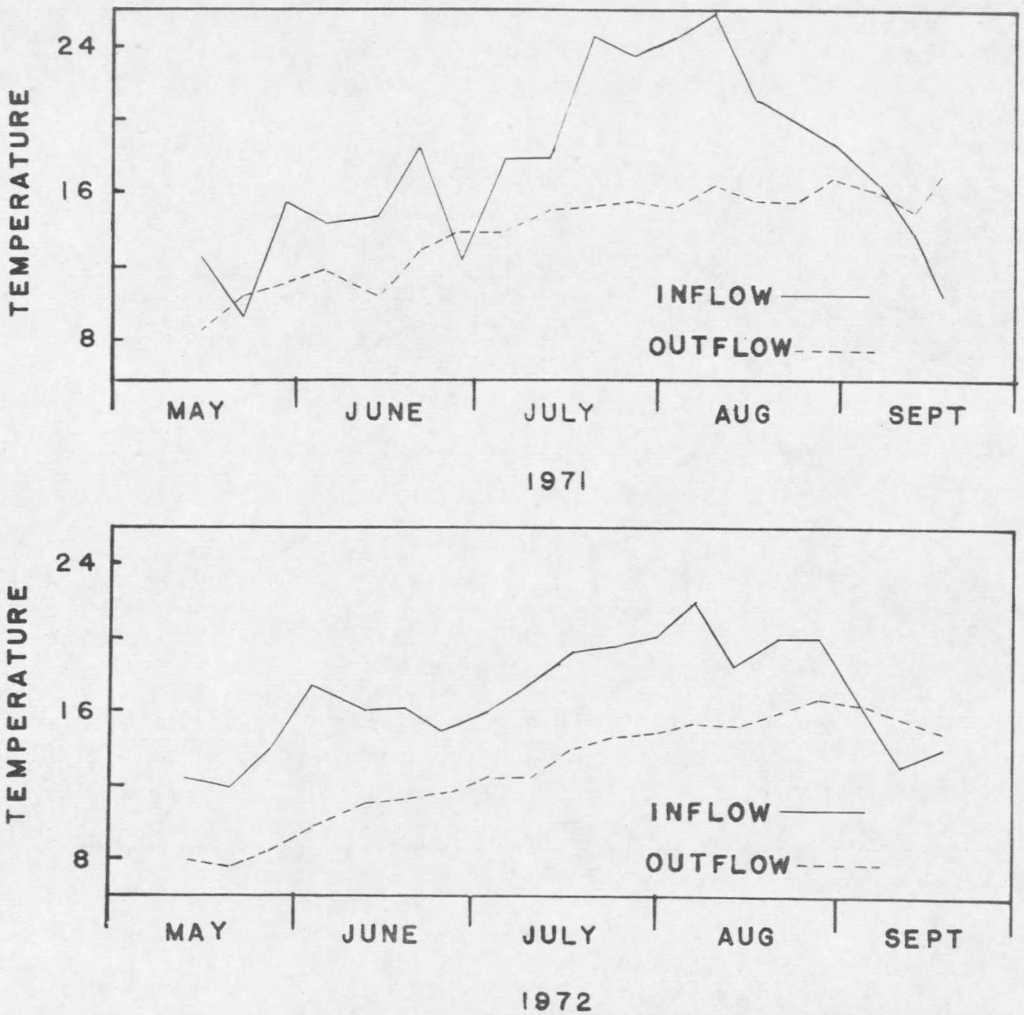

Figure 5. Seasonal temperature regimes (°C) of the inflow and outflow of Canyon Ferry Reservoir during the regular sampling seasons.

can be explained by the deep-water withdrawal of the outflow. This deep water, which accounted for the majority of the discharge, was not immediately affected by warming due to solar radiation. Also, there was a substantial lag from the time the relatively warm inflow entered the reservoir until that water mass reached the dam. Reservoirs generally delay outflow temperature increase in the spring and decrease in the fall since more time is needed for their relatively large volumes of water to approach air temperatures; consequently, they tend to impede ice formation and spring breakup (Neel 1963).

Specific Conductance

Because of the dilution effect of snow melt, inflow conductance was relatively low during spring runoff. Feth, Rogers, and Roberson (1964) reported specific conductance values of melted snow in the Western United States ranging from 2-42 micromhos$\cdot$cm^{-1}. During the latter part of June, inflow conductance began to increase and remained relatively high for the remainder of the sampling season. The ranges and averages of specific conductance for both the inflow and outflow are given in Tables 5 and 6.

The seasonal pattern of conductance for the outflow was inverse to the pattern for the inflow (Figure 6). In other words, the highest outflow conductivities were observed at the beginning of the sampling season and then progressively decreased through much of the remainder of the regular sampling season. There appeared to be about a 1 1/2- to

Table 5. Range and average of some chemical and physical parameters of the Missouri River, inflow, and outflow waters during the 1971 regular sampling period.

	Toston	Townsend and Inflow	Outflow
Ca^{++} ($me \cdot L^{-1}$)	1.19-2.20	1.34-2.26	1.34-2.26
	1.62	1.69	1.63
Mg^{++} ($me \cdot L^{-1}$)	0.06-0.94	0.12-0.98	0.02-0.94
	0.58	0.64	0.61
Na^{+} ($me \cdot L^{-1}$)	0.53-1.07	0.56-1.20	0.54-0.84
	0.84	0.90	0.68
K^{+} ($me \cdot L^{-1}$)	0.08-0.11	0.09-0.15	0.07-0.10
	0.10	0.11	0.08
Total Alkalinity	1.55-2.85	1.60-2.95	1.85-2.70
($me \cdot L^{-1}$)	2.22	2.24	2.15
$SO_4^{=}$ ($me \cdot L^{-1}$)	0.30-0.85	0.55-0.83	0.46-0.62
	0.57	0.67	0.52
Cl^{-} ($me \cdot L^{-1}$)	0.12-0.26	0.12-0.28	0.16-0.21
	0.18	0.19	0.17
F^{-} ($me \cdot L^{-1}$)	0.03-0.07	0.03-0.06	0.03-0.05
	0.05	0.05	0.04
NH_3-N ($\mu g \cdot L^{-1}$)	1-59	0-58	1-141
	17	22	37
NO_2^{-}-N ($\mu g \cdot L^{-1}$)	0-11	0-6	0-17
	3	2	4
NO_3^{-}-N ($\mu g \cdot L^{-1}$)	0-78	0-97	60-185
	20	44	122
Ortho-P ($\mu g \cdot L^{-1}$)	0-45	0-37	0-86
	16	15	38
Total-P ($\mu g \cdot L^{-1}$)	36-175	21-242	48-108
	55	59	69
Specific Conductance	214-421	204-433	265-419
($\mu mhos \cdot cm^{-1}$)	305	318	317
pH (Range)	7.50-8.90	7.35-8.90	7.15-8.30
Turbidity (JTU)	2.8-105.0	1.9-77.0	2.0-7.4
	13.8	12.3	4.9
Temperature (°C)	9.0-23.5	9.4-25.5	8.5-17.0
	16.9	17.5	14.0

Table 6. Range and average of some chemical and physical parameters of the Missouri River, inflow, and outflow waters during the 1972 regular sampling period.

	Toston	Townsend and Inflow	Outflow
Ca^{++} ($me \cdot L^{-1}$)	1.12-2.12	1.12-2.20	1.56-2.12
	1.70	1.76	1.77
Mg^{++} ($me \cdot L^{-1}$)	0.32-1.34	0.40-1.12	0.64-1.04
	0.74	0.77	0.75
Na^{+} ($me \cdot L^{-1}$)	0.36-0.92	0.55-0.95	0.60-0.93
	0.65	0.74	0.70
K^{+} ($me \cdot L^{-1}$)	0.08-0.09	0.08-0.09	0.06-0.09
	0.08	0.08	0.08
Total Alkalinity	1.50-3.00	1.50-3.05	1.95-2.70
($me \cdot L^{-1}$)	2.31	2.34	2.27
$SO_4^{=}$ ($me \cdot L^{-1}$)	0.42-0.76	0.41-0.83	0.46-0.77
	0.70	0.73	0.72
Cl^{-} ($me \cdot L^{-1}$)	0.10-0.26	0.11-0.27	0.17-0.29
	0.19	0.20	0.23
F^{-} ($me \cdot L^{-1}$)	0.01-0.06	0.01-0.06	0.05-0.05
	0.04	0.04	0.05
NH_3-N ($\mu g \cdot L^{-1}$)	0-66	0-64	3-80
	25	22	31
NO_2^{-}-N ($\mu g \cdot L^{-1}$)	0-8	0-8	0-8
	2	2	3
NO_3^{-}-N ($\mu g \cdot L^{-1}$)	0-78	0-123	22-141
	14	39	82
Ortho-P ($\mu g \cdot L^{-1}$)	6-90	3-50	13-87
	26	22	42
Total-P ($\mu g \cdot L^{-1}$)	45-170	36-146	39-103
	77	64	69
Specific Conductance	207-399	214-421	294-395
($\mu mhos \cdot cm^{-1}$)	316	329	336
pH (Range)	7.50-8.56	7.50-8.56	7.50-8.10
Turbidity (JTU)	3.0-40.0	3.0-44.0	1.0-7.0
	10.7	11.3	3.3
Temperature (°C)	11.2-22.0	11.8-21.8	7.5-16.8
	16.5	16.8	13.0

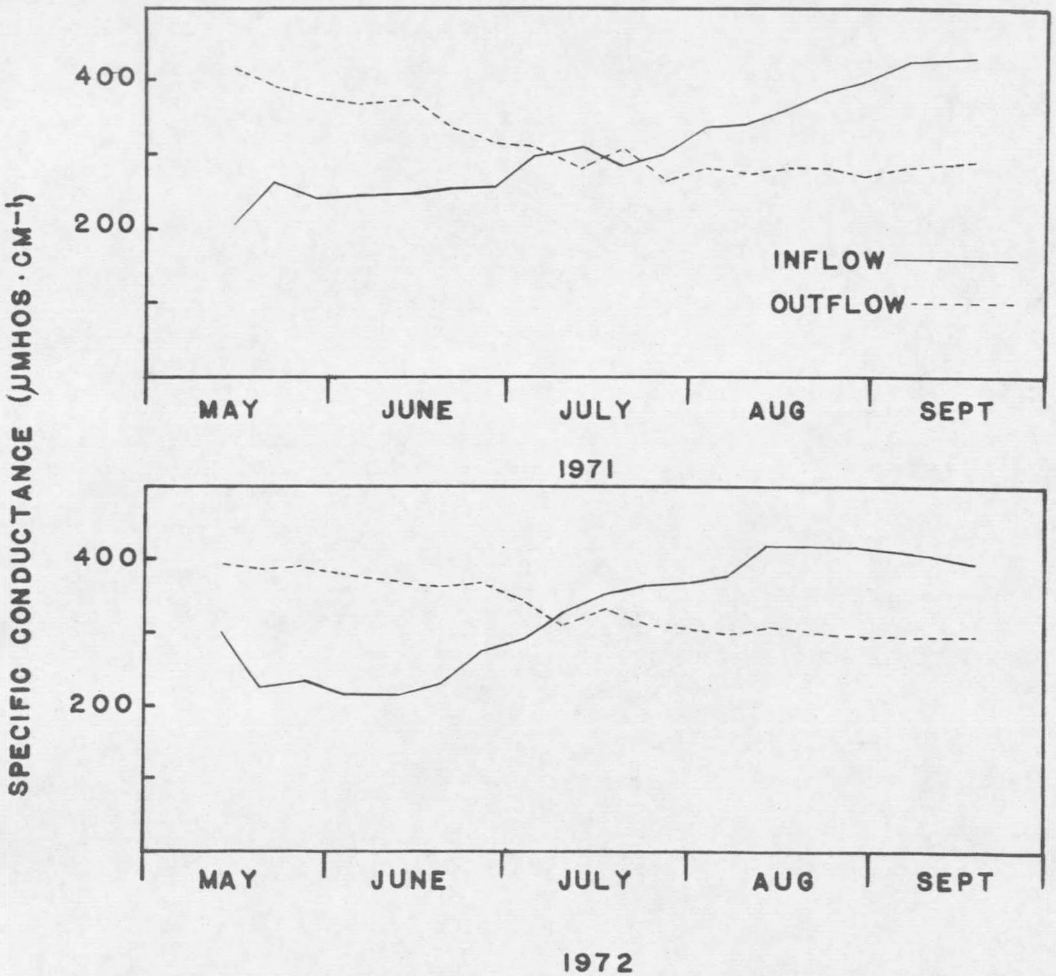

Figure 6. Seasonal variation of specific conductance in the inflow and outflow of Canyon Ferry Reservoir during the regular sampling seasons.

2-month lag for the spring inflow waters to substantially dilute the more highly conductive outflow waters (Figure 6). This would be expected since a major reservoir effect is to increase the time for passage of any chemically distinct seasonal flow (inflow) to any downstream site (outflow) (Neel 1963).

Cations and Anions

Tables 5 and 6 include a list of the ranges and averages of the major cations and anions found in the Missouri River.

The order of abundance of cations in the Missouri River was $Ca^{++} > Na^{+} \simeq Mg^{++} > K^{+}$, whereas Hutchinson (1957) reports that the mean freshwater of the world's river systems is $Ca^{++} > Mg^{++} > Na^{+} > K^{+}$. The source of the relatively high sodium concentrations in the Missouri River was probably the Madison River since sodium was by far its most abundant cation (Martin 1967). The order of abundance of anions was $HCO_3^{-} > SO_4^{=} > Cl^{-} > F^{-}$ which corresponds to what Hutchinson (1957) reports to be the normal situation for freshwaters. The inflow and outflow of Canyon Ferry could be characterized as bicarbonate water with calcium as the most abundant cation.

During 1971 average concentrations of sodium, potassium, sulfate, chloride, and fluoride appeared to be lower in the outflow than in the inflow. The decrease in the outflow concentrations was due to dilution rather than a non-conservative behavior (Sverdrup et al. 1942) of these ions. During 1972 the average concentrations of the various cations and anions of the inflow and outflow were nearly equal.

pH

The pH of the inflow was generally low (below pH 8.0) throughout spring runoff and then increased to pH 8.3 or above for the remainder of the summer. When flow rate is low and water is clear, the periphyton undergo their most active growth, but at times of high runoff and high turbidity, algal populations can be reduced to extremely low levels due to low light penetration and scouring effects (Hynes 1970 and Douglas 1958). Gumtow (1955) found that scouring action of runoff water in May and June from the West Gallatin River, Montana, almost completely removed periphyton from the stones and recovery was not evident until July. Therefore, the higher pH of the inflow after runoff subsided likely was associated with an increased rate of primary production which resulted from more abundant periphyton populations.

Nutrient Concentrations and Loads of the Headwater Streams of the Missouri River in Comparison to the Missouri River at Toston

Nutrient concentrations and loads were determined for the Missouri River headwater streams (Jefferson, Madison, and Gallatin rivers) during 7 July - 7 September 1971. The Jefferson, Madison, and Gallatin rivers contributed approximately 33%, 47%, and 20%, respectively, of the total Missouri River flow at Toston for this period. Tables 7 and 8 present data on the nutrient concentrations and loads of the headwater streams and the Missouri River at Toston.

Table 7. Nutrient concentrations ($\mu g \cdot L^{-1}$ NO_3^--N, NH_3-N, and ortho-P) of the Jefferson, Madison, and Gallatin rivers compared to those of the Missouri River at Toston during 7 July - 7 September 1971 (average concentrations).

River	NO_3^--N	NH_3-N	Ortho-P
Jefferson	1	21	6
Madison	2	22	19
Gallatin	95	23	24
Missouri (Toston)	10	11	15

Table 8. Nutrient loads (kg NO_3^--N, NH_3-N, and ortho-P) of the Jefferson, Madison, and Gallatin rivers compared to those of the Missouri River at Toston during 7 July - 7 September 1971.

River	NO_3^--N	NH_3-N	Ortho-P
Gallatin	14,046	3,069	3,465
Madison	642	8,244	6,659
Jefferson	291	6,053	1,863
Total	14,979	17,366	11,987
Missouri (Toston)	8,226	10,072	12,230
Difference	-6,753	-7,294	+243

Concentrations of ammonia in the three headwater streams were similar; however, because of differences between volumes, the relative loads were Madison > Jefferson > Gallatin.

Concentrations of nitrate and ortho-phosphorus in the Jefferson were minimal. The Madison also had only minimal concentrations of nitrate, but carried three times the concentration of ortho-phosphorus found in the Jefferson. The highest concentrations of both nitrate and ortho-phosphorus in the three streams occurred in the Gallatin. The discharge of domestic sewage from Bozeman can partially explain the higher concentrations of nitrate and ortho-phosphorus in the Gallatin (Stuart et al. 1974).

When weighted averages of the nutrients for the three headwater streams and the Missouri River at Toston are computed, two findings are particularly significant. First, the ortho-phosphorus load at Toston was about the same as it was at the confluence of the three streams at the headwaters of the Missouri River. Second, both the nitrate and ammonia loads were substantially lower at Toston than at the headwaters. This indicates that much of the inorganic nitrogen was utilized between the headwaters and Toston and never reached Canyon Ferry Reservoir.

Nutrient Concentrations and Loads of the Missouri River at Toston and Townsend

Table 9 presents average concentrations of nutrients found at Toston and Townsend during the spring-summer periods of 1971 and 1972

Table 9. A comparison of the nutrient concentrations ($\mu g \cdot L^{-1}$ NH_3-N, NO_3^--N, and ortho-P) in the Missouri River at Toston and Townsend.

Date	Location	Nitrate-Nitrogen Average	Nitrate-Nitrogen Range	Ammonia-Nitrogen Average	Ammonia-Nitrogen Range	Ortho-Phosphorus Average	Ortho-Phosphorus Range
15 May - 18 September 1971	Toston	20	0- 78	17	1-59	16	0-45
	Townsend	44	0- 97	22	0-58	15	0-37
13 May - 18 September 1972	Toston	14	0- 78	25	0-66	26	6-90
	Townsend	39	0-123	22	0-64	22	3-50
21 October 1972 26 April 1973	Toston	102	14-204	6	0-16	27	9-42
	Townsend	112	28-250	6	0-23	32	20-48

and the winter period of 1972-1973.

During each spring-summer period, the nitrate concentration was 120-179% higher at Townsend than at Toston. The same trend occurred in the winter, although the magnitude of the increase was much less. The minimum concentrations of nitrate at these two stations occurred during August when the flow and turbidity were both low. The reason for this situation could have been a rapid uptake of nitrate by periphytic algae during those times of optimal light penetration. The high concentrations during the winter might have been due to low biological uptake associated with low light intensities and temperatures.

Ammonia concentrations were slightly higher at Townsend than at Toston during 1971, while the inverse was observed during 1972. Maximum ammonia concentration occurred in May and June each year and then remained relatively low until the following spring.

Total and ortho-phosphorus concentrations were highest at both stations during June each year and were associated with peak runoff and high turbidities. Minimum concentrations occurred during the late summer and fall during low flows.

Table 10 presents nitrate, ammonia, and ortho-phosphorus loads for Toston and Townsend during the periods of 15 May 1971 - 18 September 1971 and 13 May 1972 - 12 May 1973.

Diversion of Missouri River water for irrigation of the Townsend Valley occurred above the Toston station. Return flows of this

Table 10. A comparison of the nutrient loads (kg NH_3-N, NO_3^--N, and ortho-P) for the Missouri River at Toston and Townsend.

Date	Location	NO_3^--N	NH_3-N	Ortho-P	NO_3^--N: Ortho-P	NO_3^- + NH_3-N: Ortho-P
15 May-18 September 1971	Toston	99,976	60,674	58,348	3.79	6.09
	Townsend	153,388	83,209	59,975	5.65	8.72
	Difference	+53,412	+22,535	+1,627		
13 May 1972 - 12 May 1973	Toston	294,354	92,504	155,553	4.19	5.50
	Townsend	378,540	95,221	162,171	5.16	6.46
	Difference	+84,186	+2,717	+6,618		

Table 11. A comparison of the phosphorus fractions (kg total-P, combined-P, and ortho-P) for the Missouri River at Toston and Townsend.

Date	Location	Total-P	Combined-P	Ortho-P
21 June - 18 September 1971	Toston	113,394	78,939	34,455
	Townsend	139,844	109,515	30,329
	Difference	+26,450	+30,576	-4,126
12 June 1972-26 April 1973	Toston	307,555	199,940	107,615
	Townsend	276,681	170,486	106,195
	Difference	-30,874	-29,454	-1,420

irrigation water entered the Missouri River between Toston and Townsend; therefore, a comparison of these two stations gives an estimate of agricultural input to the river from the Townsend Valley above Canyon Ferry Reservoir. Although 1971 data included only the mid-May to mid-September period, they still encompassed the irrigation season.

Nitrate loading each year was substantially greater at Townsend than at Toston, i.e. 53% greater in 1971 and 29% greater in 1972. The molar N:P ratio was also greater at Townsend. There was a 37% greater loading of ammonia at Townsend than at Toston during 1971, while in 1972 Townsend carried only slightly more than Toston. With regard to ortho-phosphorus, there was only a 3-4% greater loading at Townsend than at Toston. Leaching of fertilized land by irrigation return flows was the most probable cause of the greater nitrate loading at Townsend. The relatively high solubility of nitrate and ammonia and the low solubility of phosphorus in soil percolates could explain the relative differences in nutrient loads between Toston and Townsend (Biggar and Corey 1969).

Table 11 presents a comparison of the phosphorus fractions at Toston and Townsend. During 1971 combined phosphorus loading was substantially greater (39%) at Townsend than at Toston, while the ortho-phosphorus loading was 12% less than the ortho-phosphorus load at Toston. The trend of combined phosphorus loading was inverse in 1972 compared to 1971. Total phosphorus at Townsend was 123% and 90% of the total phosphorus carried by the Missouri River at Toston during 1971 and 1972, respectively. That situation could have been related to stream flow rather than agricultural activity since there was a 28% higher flow in 1971 than in 1972.

Nutrient Concentration and Loads of the Inflow and Outflow of Canyon Ferry Reservoir.

Ranges and averages for nutrient concentrations of the inflow and outflow of Canyon Ferry are given in Table 12.

During each summer there was a two- to three-fold increase in the concentration of nitrate discharged from Canyon Ferry as compared to the inflow. The same trend was observed in the winter, although the magnitude of the difference was much smaller than in the summer. The most logical explanation for those conditions was the biological fixation of nitrogen by blue-green algae, viz. *Aphanizomenon*, within the reservoir during the summer of each year. Subsequent decomposition and mineralization of this planktonic organic material would have occurred in the lower strata of water and a large portion of the nitrogen fixed would then have been lost as a result of the deep-water withdrawal from Canyon Ferry Dam.

Ammonia concentrations were also higher in the outflow than in the inflow but to a much lesser extent than nitrate. This situation was also associated with the deep-water withdrawal of ammonia resulting from ammonification of organic matter in the lower depths of the reservoir.

Table 12. A comparison of the nutrient concentrations (µg·L^{-1} NH_3-N, NO_3^--N, and ortho-P) in the inflow and outflow of Canyon Ferry Reservoir.

Date	Location	Nitrate-Nitrogen Average	Nitrate-Nitrogen Range	Ammonia-Nitrogen Average	Ammonia-Nitrogen Range	Ortho-Phosphorus Average	Ortho-Phosphorus Range
15 May - 18 September 1971	Inflow	44	0- 97	22	0- 58	15	0-37
	Outflow	122	60-185	37	1-141	38	0-86
13 May - 18 September 1972	Inflow	39	0-123	22	0- 64	22	3-50
	Outflow	82	22-141	31	3- 80	42	13-87
21 October 1972 - 26 April 1973	Inflow	112	28-250	6	0- 23	32	20-48
	Outflow	140	48-181	20	0- 75	40	31-56

The most notable finding concerning ortho-phosphorus was the substantially higher concentration in the outflow when compared to the inflow. The concentration of ortho-phosphorus in the outflow ranged from 25-153% greater than that found in the inflow. This trend was accompanied by a drop in the molar ratio of total phosphorus to ortho-phosphorus from 2.38 to 4.61 at the inflow to 1.36 to 1.80 at the outflow. Hence, mineralization of combined phosphorus to ortho-phosphorus was occurring within the reservoir.

Table 13 presents nutrient loads of the inflow and outflow for spring-summer, 1971, and the calendar year beginning 13 May 1972.

During the summer of 1971, 96% more nitrate was discharged from Canyon Ferry Dam than was added at the inflow. The same phenomenon occurred during the 1972-1973 period when 53% more nitrate was found in the outflow as compared to the inflow. Ammonia behaved in the same manner; approximately 16-36% more ammonia was present in the outflow as compared to the inflow.

Data on fractionation of phosphorus species found in the inflow and outflow are presented in Table 14. While the outflow contained 93% and 77% more ortho-phosphorus than the inflow during the 1971 and 1972-1973 periods, respectively, it contained 24% less total phosphorus than the inflow during 1971 and a nearly equal amount of total phosphorus during the 1972-1973 period. Each year less than 50% of the combined phosphorus that entered Canyon Ferry was present in the outflow. The greater input

Table 13. A comparison of the nutrient loads (kg NH_3-N, NO_3^--N, and ortho-P) for the inflow and outflow of Canyon Ferry Reservoir.

Date	Location	NO_3^--N	NH_3-N	Ortho-P	NO_3-N: Ortho-P	NO_3^- + NH_3-N: Ortho-P
15 May-18 September 1971	Inflow	154,550	84,010	60,464	5.65	8.72
	Outflow	303,084	97,038	88,492	7.57	10.00
	Difference	+148,534	+13,028	+28,028		
13 May 1972-12 May 1973	Inflow	379,985	96,003	163,169	5.15	6.45
	Outflow	582,308	130,186	216,968	5.93	7.26
	Difference	+202,323	+34,183	+53,799		

Table 14. A comparison of the phosphorus fractions (kg total-P, combined-P, and ortho-P) for the inflow and outflow of Canyon Ferry Reservoir.

Date	Location	Total-P	Combined-P	Ortho-P
21 June-18 September 1971	Inflow	140,432	109,937	30,495
	Outflow	106,155	47,161	58,994
	Difference	-34,277	-62,776	+28,499
12 June 1972-26 April, 1973	Inflow	276,147	160,473	115,674
	Outflow	277,349	73,118	204,231
	Difference	+1,202	-87,355	+88,557

of combined phosphorus each year was probably associated with high runoff during June, especially in 1971. The data indicate that, on the average during the spring-summer periods, approximately 44% of the combined phosphorus that entered Canyon Ferry was discharged from the dam, while 43% was mineralized and converted to ortho-phosphorus which left the reservoir. The remainder of the combined phosphorus (12-13%) was sedimented and retained within the reservoir.

The deep-water withdrawal of Canyon Ferry is significant since it tends to prevent the accumulation of nutrients, especially nitrate and ammonia, within the reservoir. Conversely, natural lakes with surface withdrawals tend to accumulate nutrients. Eutrophication in Canyon Ferry should, therefore, be slow and depend on the kinetics of the equilibria between phosphorus in solution and phosphorus in the sediments at the mud-water interface. The role of sediment phosphorus in the process of eutrophication is complex and has been extensively reviewed by Syers et al. (1973).

The Federal Water Pollution Control Administration (1968) recommended that total phosphorus not exceed 100 $\mu g \cdot L^{-1}$ at any point within a flowing stream or 50 $\mu g \cdot L^{-1}$ where streams enter lakes or reservoirs. Based on these criteria, the inflow and outflow waters of Canyon Ferry were, on the average, within the limits for flowing waters. At certain times during the runoff season, however, total phosphorus concentrations of the inflow did exceed the limits for flowing water.

Total phosphorus concentrations of the outflow exceeded the limits on three occasions during the study. Moreover, average total phosphorus concentrations were greater than the recommended 50 $\mu g \cdot L^{-1}$ for streams that enter reservoirs. The apparent excessive loading of phosphorus into Canyon Ferry must be considered together with the design of the reservoir; i.e., the retention of phosphorus within the reservoir was reduced because of the deep-water withdrawal.

The FWPCA (1968) also recommended that inorganic nitrogen concentrations not exceed a level ten times the allowable phosphorus concentrations. During the study, average inorganic nitrogen concentrations were within the recommended limits for both flowing waters and flowing waters entering reservoirs. However, maximum inorganic nitrogen concentrations were in excess of the recommended limits for streams entering reservoirs or lakes.

Reservoir

Turbidity and Light

Perhaps the major effect of reservoirs on turbidity is to allow large amounts of sediment suspended in the inflow waters to settle out with a resultant increase in water clarity (Symons et al. 1964 and Neel 1963). The decrease in turbidity as a result of the settling of suspended solids is observed primarily in the spring during high runoff (Shelomov and Spichak 1960). During the summer, however, turbidity of the lake can be greater than that of the inflow because of plankton blooms within the lake (Entz 1972).

Figure 7 shows that Canyon Ferry acted as a sediment trap since most of the suspended sediments settled out between Stations 2 and 3 (approximately 11-12 km upstream from the dam). The seasonal regime of turbidity paralleled inflow rates except during certain times in the late summer at Stations 3 and 4 when blue-green algal blooms increased the turbidity of the surface waters.

Penetration of total visible light, mean extinction coefficients, and euphotic zone depths are depicted in Figure 8. A paired t-test indicated that each successive station, beginning with Station 4 and progressing toward Station 1, showed a significant increase in water clarity during 1971 ($p \leq 0.05$) and 1972 ($p \leq 0.07$).

The depth of the euphotic zone (compensation depth) also increased progressively from Station 4 to the dam. The average depth of the euphotic zone for each station remained quite constant between 1971 and 1972. The mean extinction coefficients (k) per meter of euphotic zone depth at Station 1 during 1957 and 1958 were 0.90 and 0.64 (Wright et al. 1974) as compared to 0.70 and 0.75 during 1971 and 1972, respectively. Water clarity at Station 1, therefore, appeared to be similar for the two periods.

Temperature and Specific Conductance

Temperature and conductivity regimes were similar throughout the

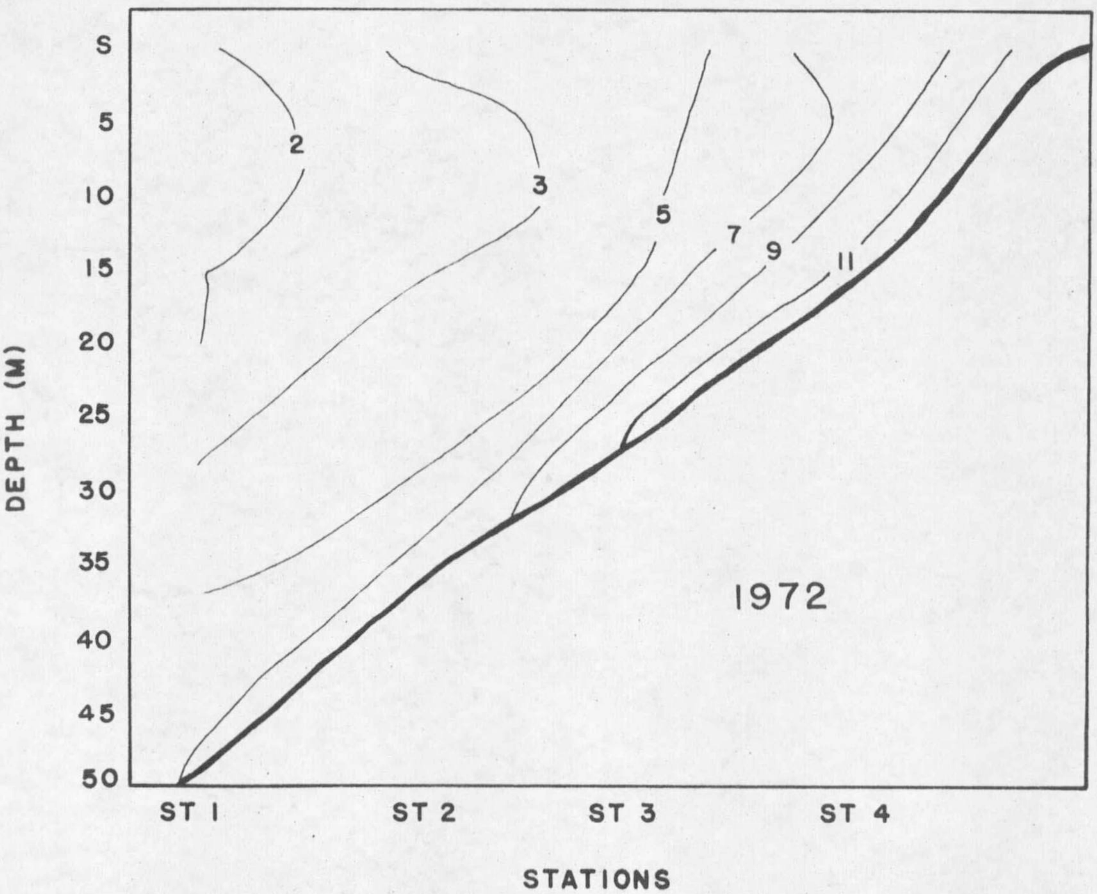

Figure 7. Average turbidity profile in Canyon Ferry Reservoir during 1972 (Jackson Turbidity Units).

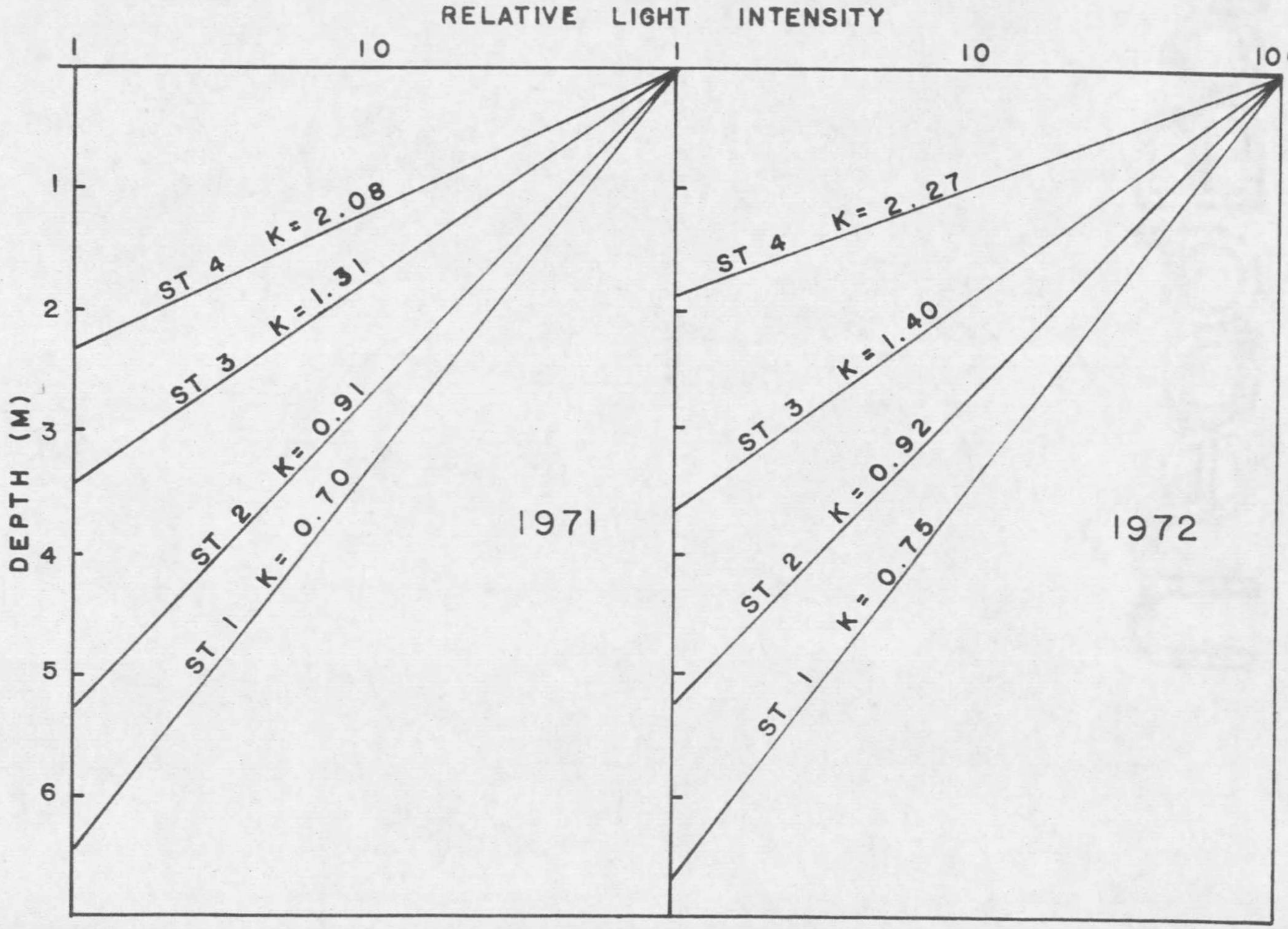

Figure 8. Penetration of total visible light, mean extinction coefficients (k), and euphotic zone depths (1% relative light intensity) in Canyon Ferry Reservoir during 1971 and 1972.

sampling period. Figure 9 portrays the seasonal temperature pattern at Station 1 during 1971 and 1972.

After ice cover left Canyon Ferry (mid-April), the reservoir began to warm rapidly from advected heat of the inflow, in addition to absorption of solar radiation at the water surface. Although quite weak, thermal stratification was already becoming established by late May and became more intense as the summer progressed, especially during 1972. At the height of the warming period (mid-August), the difference between surface and bottom temperatures was 10.9C° and 11.7C° during 1971 and 1972, respectively. The highest surface temperatures observed in Canyon Ferry were 23.3°C in 1971 and 21.9°C in 1972. On 18 September of each year the cooling process of the lake was well underway and the epilimnion extended down to a depth of 30-35 m.

Figure 9 shows the rather irregular isotherms that occurred in Canyon Ferry Reservoir. Irregular isotherms in wind-stressed lakes can be best explained by the movement of wind-induced internal seiches (Henson 1959 and Hutchinson 1957). At times Canyon Ferry was stressed by a relatively strong wind that blew directly up-lake. During stratification this wind would have caused the warmer, less dense water to be transported up-lake where it would have accumulated. This transport disrupted the hydrostatic equilibrium and at times caused an upwelling of cooler, more dense water at the windward end of the lake (Figure 10). Conductivity isoclines were similarly deflected upward toward the

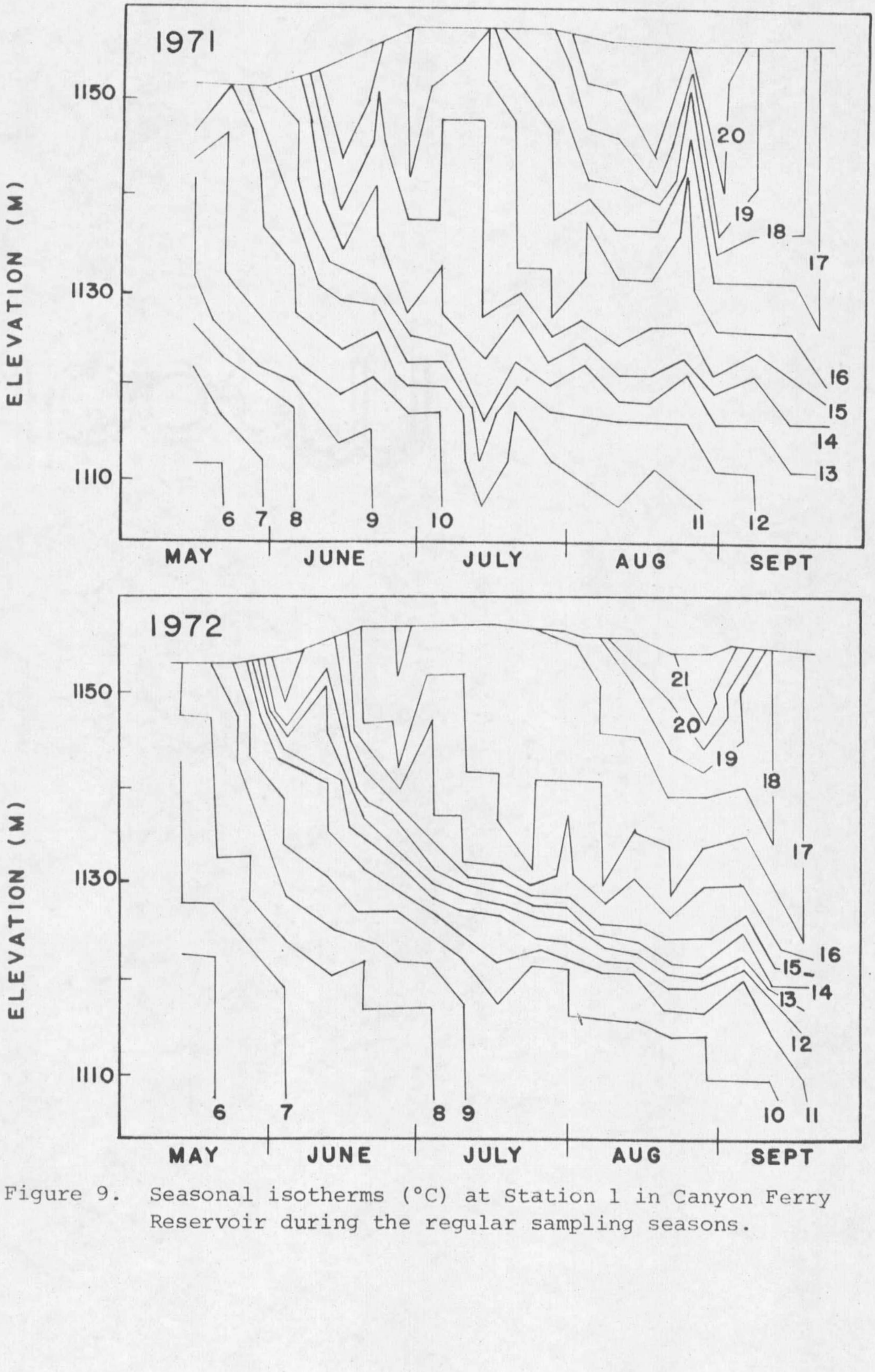

Figure 9. Seasonal isotherms (°C) at Station 1 in Canyon Ferry Reservoir during the regular sampling seasons.

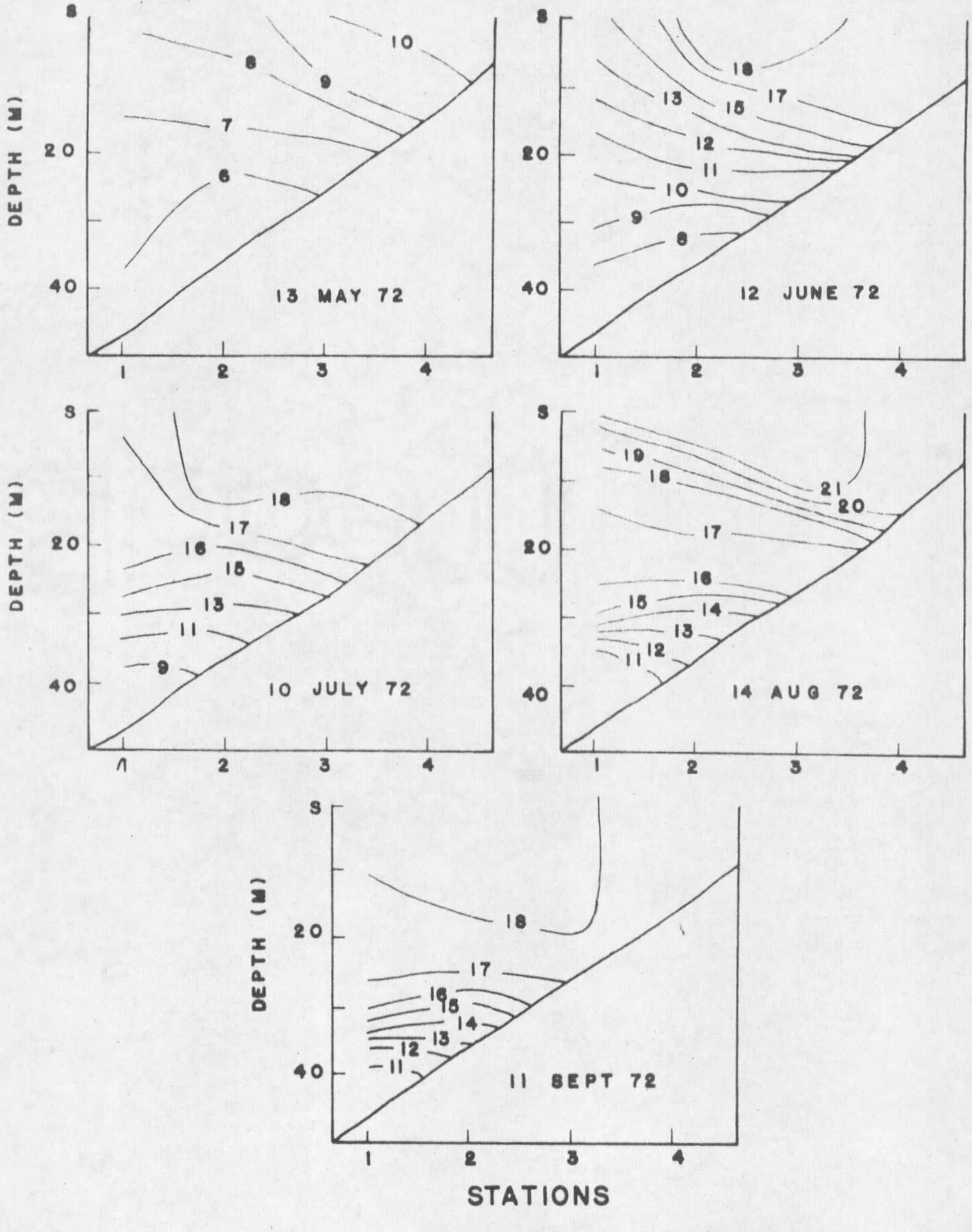

Figure 10. Seasonal isotherms (°C) in Canyon Ferry Reservoir during 1972.

surface (Figure 11). When the wind subsided, an internal seiche was probably initiated which caused the irregular isotherms shown in Figure 9. During 1972, only the isotherms and conductivity isoclines of the epilimnion were deflected upward, whereas during 1971 the isotherms and conductivity isoclines of the lower strata were also somewhat affected because of less intense stratification.

Although quite well defined at Station 1, especially during 1972, stratification became less stable progressing up-lake. Homothermal conditions were often present at Station 4 because of its shallow depth and exposure to strong wind action.

At the onset of each sampling season, the coolest temperatures in Canyon Ferry were 7°C in 1971 and 6°C in 1972. By 18 September of each successive year, however, the coolest temperatures in the reservoir were 13°C and 11°C, respectively. This, in addition to its summer heat incomes of 27,726 $cal \cdot cm^{-2}$ during 1971 and 24,294 $cal \cdot cm^{-2}$ during 1972, demonstrate Canyon Ferry's effectiveness as a heat trap. As discussed by Wright (1967), the design of reservoirs with relatively warm summer inflow waters and deep-water discharges causes them to be efficient heat traps.

Generally, patterns of conductivity in Canyon Ferry were similar to the previously discussed temperature patterns. By late May there was evidence of thermally-induced chemical stratification. The greatest difference in conductivity between the surface and bottom

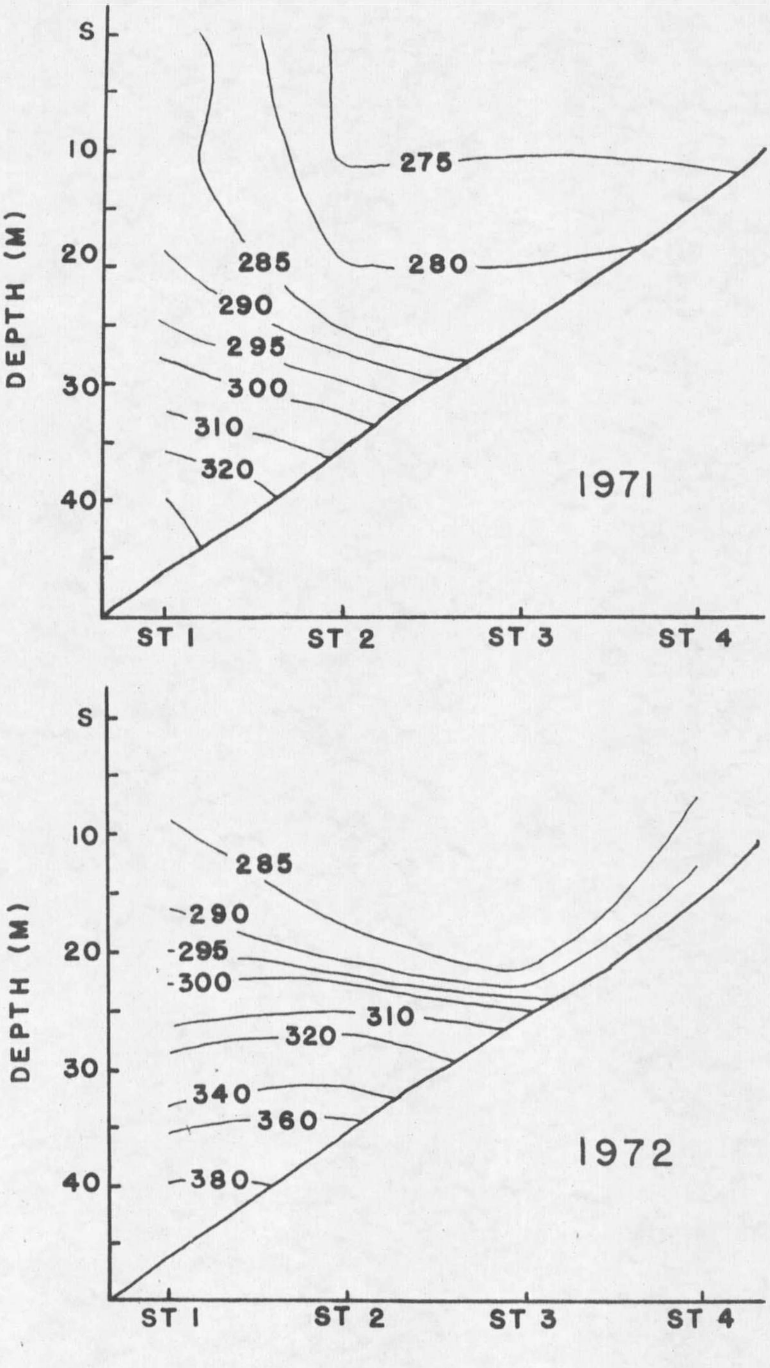

Figure 11. Average conductivity isoclines (μmhos$\cdot$cm^{-1}) at all stations during thermal stratification.

was 80 and 114 μmhos$\cdot$cm^{-1} during 1971 and 1972, respectively. As with thermal stratification, chemical stratification became less stable progressing upstream toward Station 4.

Conductivity in the reservoir was relatively high during the early spring but became much lower during late spring to early summer because of dilution from the high runoff. When runoff subsided, the conductivity of the inflow increased and the conductivity of the reservoir began to rise. On the average, conductivity of the reservoir was higher during 1972 than in 1971 (Tables 15 and 16).

Oxygen and pH

Relatively high oxygen concentrations occurred throughout the water column during the early part of the sampling season (Figure 12). The non-conservative behavior of oxygen was observed with the onset of thermal stratification when concentrations in the hypolimnion rapidly declined because of decomposition of organic matter. As the season progressed, the low oxygen isoclines moved up-lake as well as upward in the water column. By 21 August 1972 the 2 mg$\cdot$L^{-1} isocline extended from Station 1 to Station 4. A similar pattern occurred during 1971. The lowest oxygen concentrations found within the reservoir were 0.5 mg $O_2\cdot L^{-1}$ in 1971 and 0.9 mg $O_2\cdot L^{-1}$ in 1972 and were encountered on the bottom at Station 1. The lowest concentrations found at Station 4, which was usually well mixed, were 0.9 and 1.2 mg $O_2\cdot L^{-1}$ during 1971 and 1972, respectively. This indicated that, because of decomposition,

Table 15. Range and average of some chemical and physical parameters in Canyon Ferry Reservoir during the 1971 regular sampling season.

	Station 1	Station 2	Station 3	Station 4
Ca^{++} ($me \cdot L^{-1}$)	1.30-2.52	1.20-2.42	1.26-1.94	1.26-1.80
	1.64	1.59	1.51	1.52
Mg^{++} ($me \cdot L^{-1}$)	0.18-0.97	0.04-1.10	0.04-1.00	0.09-0.76
	0.61	0.56	0.56	0.52
Na^{+} ($me \cdot L^{-1}$)	0.51-0.84	0.55-0.81	0.49-0.70	0.50-0.84
	0.65	0.63	0.61	0.66
K^{+} ($me \cdot L^{-1}$)	0.04-0.11	0.05-0.09	0.01-0.07	0.01-0.14
	0.07	0.07	0.05	0.07
Total Alkalinity ($me \cdot L^{-1}$)	1.65-2.79	1.75-2.76	1.75-2.50	1.70-2.40
	2.14	2.06	1.97	1.97
$SO_4^{=}$ ($me \cdot L^{-1}$)	0.25-0.62	0.27-0.52	0.36-0.47	0.35-0.49
	0.44	0.41	0.42	0.43
Cl^{-} ($me \cdot L^{-1}$)	0.14-0.25	0.14-0.24	0.12-0.18	0.12-0.28
	0.18	0.16	0.15	0.17
F^{-} ($me \cdot L^{-1}$)	0.03-0.06	0.03-0.05	0.03-0.05	0.03-0.05
	0.04	0.04	0.04	0.04
NH_3-N ($\mu g \cdot L^{-1}$)	0-164	0-119	1-111	2-89
	26	27	31	36
NO_2^{-}-N ($\mu g \cdot L^{-1}$)	0-32	0-20	0-22	0-20
	5	4	5	5
NO_3^{-}-N ($\mu g \cdot L^{-1}$)	0-378	0-308	0-261	0-200
	120	93	72	48
Ortho-P ($\mu g \cdot L^{-1}$)	0-104	1-86	0-93	1-88
	35	30	28	25
Total-P ($\mu g \cdot L^{-1}$)	13-167	17-169	20-179	32-167
	65	59	61	66
Specific Conductance ($\mu mhos \cdot cm^{-1}$)	247-412	241-417	251-387	245-342
	314	301	287	278
pH (Range)	4.85-8.95	6.85-8.80	7.10-8.75	7.05-8.70
Turbidity (JTU)	0.9-33.0	0.9-25.5	1.2-57.0	2.8-45.0
	5.3	5.1	8.0	10.8
Temperature (°C)	6.4-23.3	7.0-22.6	8.8-22.7	13.0-22.7
	14.1	15.2	16.1	18.3
Oxygen ($mg \cdot L^{-1}$)	0.5-11.8	1.5-10.2	1.3-10.2	0.9-10.2
	6.4	6.9	7.4	7.9

Table 16. Range and average of some chemical and physical parameters in Canyon Ferry Reservoir during the 1972 regular sampling season.

	Station 1	Station 2	Station 3	Station 4
Ca^{++} ($me \cdot L^{-1}$)	1.40-2.28 1.79	1.46-2.20 1.70	1.32-2.20 1.65	1.16-2.24 1.63
Mg^{++} ($me \cdot L^{-1}$)	0.42-1.02 0.74	0.24-1.30 0.69	0.38-0.86 0.64	0.28-1.24 0.59
Na^{+} ($me \cdot L^{-1}$)	0.57-0.96 0.72	0.52-0.93 0.65	0.46-0.76 0.59	0.46-0.73 0.55
K^{+} ($me \cdot L^{-1}$)	0.06-0.10 0.08	0.06-0.10 0.07	0.06-0.09 0.07	0.06-0.08 0.07
Total Alkalinity ($me \cdot L^{-1}$)	1.80-2.80 2.42	1.80-2.80 2.16	1.70-2.70 2.09	1.45-2.65 2.08
$SO_4^{=}$ ($me \cdot L^{-1}$)	0.42-0.88 0.66	0.43-0.82 0.60	0.42-0.66 0.59	0.44-0.63 0.54
Cl^{-} ($me \cdot L^{-1}$)	0.15-0.32 0.23	0.16-0.31 0.20	0.16-0.25 0.18	0.14-0.20 0.17
F^{-} ($me \cdot L^{-1}$)	0.04-0.06 0.05	0.04-0.06 0.05	0.03-0.05 0.04	0.02-0.05 0.04
NH_3-N ($\mu g \cdot L^{-1}$)	0-250 31	0-139 30	3-210 38	1-250 51
NO_2^{-}-N ($\mu g \cdot L^{-1}$)	0-28 4	0-14 3	0-20 5	0-22 8
NO_3^{-}-N ($\mu g \cdot L^{-1}$)	0-265 83	0-265 65	0-215 46	0-262 31
Ortho-P ($\mu g \cdot L^{-1}$)	0-165 35	0-109 31	2-123 31	2-94 31
Total-P ($\mu g \cdot L^{-1}$)	21-250 70	21-137 66	29-197 75	29-165 82
Specific Conductance ($\mu mhos \cdot cm^{-1}$)	271-430 334	260-393 316	258-392 286	212-377 295
pH (Range)	7.40-8.48	7.45-8.72	7.15-8.69	7.10-8.78
Turbidity (JTU)	0.8-20.0 3.2	0.5-18.0 3.7	1.0-40.0 6.0	2.0-18.0 8.7
Temperature (°C)	5.5-21.7 13.2	5.2-21.5 14.2	6.8-21.7 15.9	9.0-21.6 16.4
Oxygen ($mg \cdot L^{-1}$)	0.9-13.0 6.8	1.7-12.2 7.2	1.8-12.6 7.2	1.2-12.3 8.2

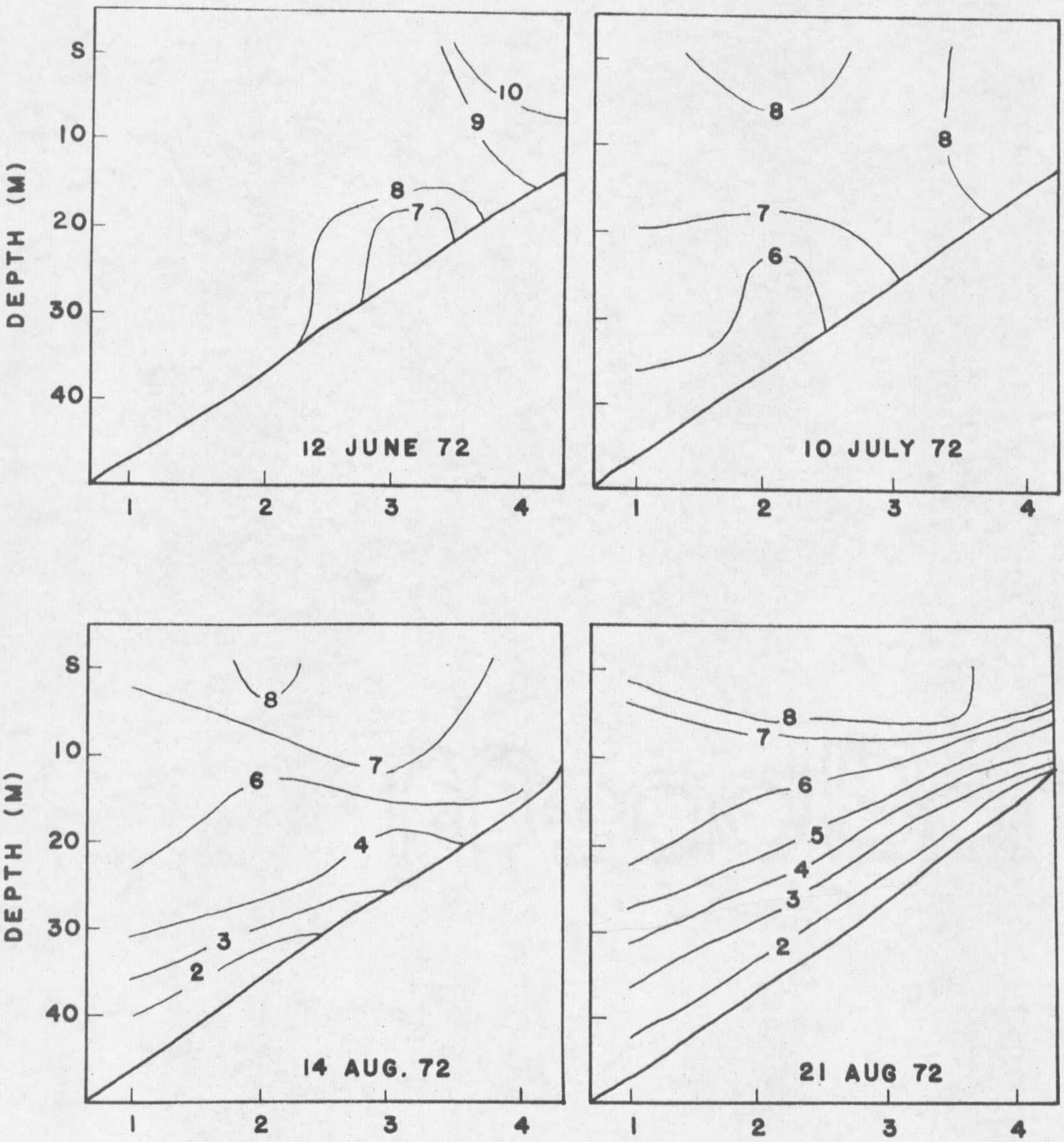

Figure 12. Oxygen isoclines ($mg \cdot L^{-1}$) on selected dates to show oxygen depletion in Canyon Ferry Reservoir during 1972.

oxygen was consumed at a rate faster than could be replenished by the downward turbulent diffusion of oxygen.

The areal hypolimnetic deficit (Hutchinson 1938) has been used to estimate the trophic state of lakes. As used here, it is an estimate of the areal rate of oxygen metabolically consumed between the onset of thermal stratification and the height of summer stagnation. The areal hypolimnetic oxygen deficits observed for Canyon Ferry during 1971 and 1972 were 0.049 and 0.079 mg $O_2 \cdot cm^{-2} \cdot day^{-1}$, respectively. Wright et al. (1974) reported values in Canyon Ferry of 0.084 mg $O_2 \cdot cm^{-2} \cdot day^{-1}$ in 1957 and 0.085 mg $O_2 \cdot cm^{-2} \cdot day^{-1}$ in 1958. Hutchinson (1938) regarded lakes having deficits of $>$ 0.033 mg $O_2 \cdot cm^{-2} \cdot day^{-1}$ as eutrophic, while Mortimer (1957) suggested 0.055 mg $O_2 \cdot cm^{-2} \cdot day^{-1}$ as the lower limits of eutrophy. Based on these arbitrary limits, Canyon Ferry bordered on the lower limits of eutrophy; however, the data of 1957-1958 and 1971-1972 indicate that Canyon Ferry had not become more eutrophic during that time span.

Patterns of pH changes were similar to those for oxygen. Early in the season, the water was relatively homogeneous with regard to pH; but with the onset of thermal stratification, the pH of the hypolimnion began to decrease. On 5 July 1971 the pH was 4.85 on the bottom at Station 1. On all other occasions, the pH was above 7 at all stations. The highest pH observed was 8.95 in 1971 and 8.78 in 1972. Generally, pH within the euphotic zone was higher during late July and August.

Phytoplankton standing crops, primary production, and temperature were also greatest at this time.

Cations and Anions

The order of abundance of cations and anions in the reservoir was essentially the same as that for the inflow and outflow (Tables 15 and 16). Canyon Ferry could be characterized as a bicarbonate water with calcium as the most abundant cation. Bicarbonate accounted for nearly all the total alkalinity in Canyon Ferry because at the pH range encountered only small amounts of carbonate were present.

Table 17 presents the average seasonal distribution of cations and anions during 1972. Perhaps the most notable change was the extent of the decrease in total alkalinity and calcium through early August. This situation resulted from the storage of relatively dilute spring runoff water. After early August the cations and anions began to increase toward their earlier levels. A similar seasonal pattern occurred during 1971.

Vollenweider (1970) tentatively classified the trophic state of several lakes according to the total alkalinity decrease in the epilimnion during the summer. According to his classification, lakes with a summer decrease in epilimnetic alkalinity greater than 0.60 $me \cdot L^{-1}$ were eutrophic. Epilimnetic alkalinity decreases of 0.8 $me \cdot L^{-1}$ in 1971 and 0.7 $me \cdot L^{-1}$ in 1972 suggest that Canyon Ferry was a eutrophic lake. Vollenweider's reasoning was based on sufficient carbon dioxide removal

Table 17. Average seasonal distribution of cations and anions ($me \cdot L^{-1}$) in Canyon Ferry Reservoir during 1972.

Date	Alk.	$SO_4^{=}$	Cl^-	F^-	Total Anions	Ca^{++}	Mg^{++}	Na^+	K^+	Total Cations
May 13	2.68					2.17	0.77			
May 20	2.60					1.97	0.86			
May 27	2.56					1.96	0.75			
June 3	2.40					1.79	0.76			
June 12	2.40	0.61	0.25	0.04	3.30	1.73	0.72	0.76	0.09	3.30
June 19	2.04					1.78	0.69			
June 26	2.03					1.76	0.65			
July 3	2.03					1.76	0.64			
July 10	1.94	0.54	0.19	0.05	2.72	1.64	0.57	0.57	0.07	2.85
July 17	2.09					1.68	0.56			
July 24	1.96					1.58	0.65			
July 31	1.98					1.59	0.71			
Aug. 7	1.97	0.61	0.19	0.04	2.81	1.55	0.69	0.63	0.07	2.94
Aug. 14	2.18					1.59	0.69			
Aug. 21	2.21					1.59	0.70			
Aug. 28	2.10					1.65	0.71			
Sept. 5	2.10	0.67	0.18	0.05	3.00	1.68	0.67	0.64	0.06	3.05
Sept. 11	2.23					1.68	0.73			
Sept. 18	2.31					1.76	0.77			

by photosynthesis to precipitate calcium carbonate which would lower the alkalinity. However, in the case of Canyon Ferry, the alkalinity decrease resulted from storage of dilute runoff water rather than calcium precipitation. Negligible concentrations of carbonate further demonstrate the insignificance of calcium carbonate precipitation in the epilimnion of Canyon Ferry. This evidence shows that reservoirs such as Canyon Ferry do not necessarily fit Vollenweider's classification. Hence, caution must be taken rather than unequivocally accepting and applying classification schemes such as this to all lakes and reservoirs.

Nutrients

The range and average concentrations of nutrients in Canyon Ferry are presented in Tables 15 and 16.

From the onset of each sampling season, nitrate concentrations were lowest in the upper strata of water and highest in the deeper strata. The differences between concentrations in the epilimnion and the hypolimnion became much more pronounced as each season progressed. At Station 1 on 29 May 1971 nitrate ranged from 52 $\mu g \cdot L^{-1}$ at the surface to 89 $\mu g \cdot L^{-1}$ at the bottom. On 10 August 1971 nitrate ranged from an undetectable concentration at the surface to 378 $\mu g \cdot L^{-1}$ at the bottom. Similar trends were observed each year at the other stations except Station 4 which at times became well mixed due to wind action. Generally, average nitrate concentrations for the entire water column became progressively higher from Station 4 to Station 1.

Nitrite concentrations were somewhat variable in distribution and were highest during late June, while low to undetectable concentrations occurred during late July and August.

Generally, ammonia was abundant throughout the entire water column during May and June and then generally decreased. A marked accumulation of ammonia never occurred in the hypolimnion during summer stagnation; however, on 18 September of each year concentrations ranging up to 250 $\mu g \cdot L^{-1}$ were observed near the bottom at the lower end of the reservoir. Average concentrations were similar at Stations 1 and 2 but were progressively greater at Stations 3 and 4, respectively.

The vertical distribution of ortho-phosphorus was similar to that of nitrate. During 1971 average ortho-phosphorus concentration was highest at Station 1 and lowest at Station 4, whereas during 1972 the average concentrations were the same at Stations 2, 3, and 4 and highest at Station 1. Each year average total phosphorus concentrations were highest at Station 4 and lowest at Station 2. The highest total phosphorus concentration observed was 250 $\mu g \cdot L^{-1}$ near the bottom at Station 1 on 18 September 1972.

Figures 13 and 14 show the average seasonal euphotic zone concentrations of nitrate and ortho-phosphorus together with the average seasonal standing crops of the two most abundant classes of phytoplankton, Bacillariophyceae and Myxophyceae.

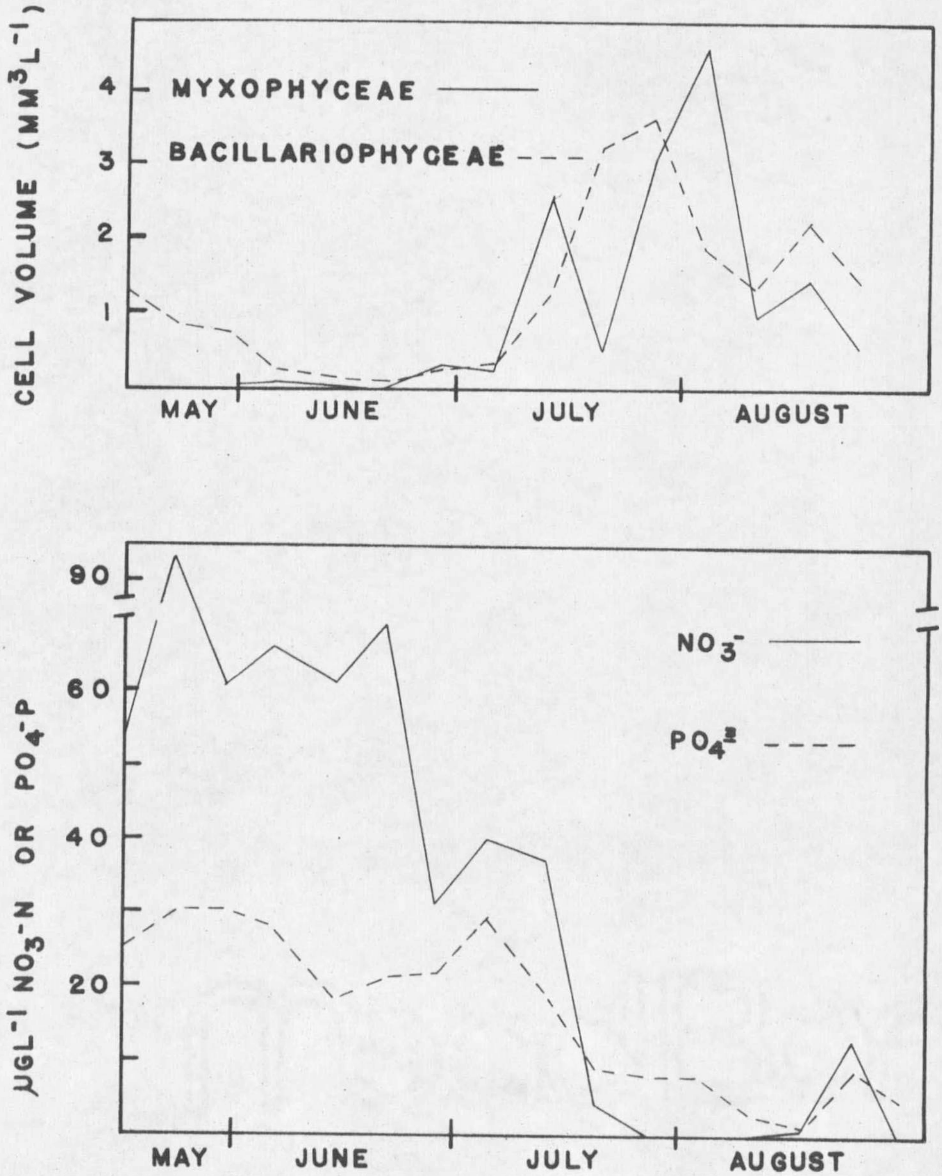

Figure 13. Average seasonal euphotic zone concentrations of nitrate and ortho-phosphorus together with average standing crops of Bacillariophyceae and Myxophyceae during 1971.

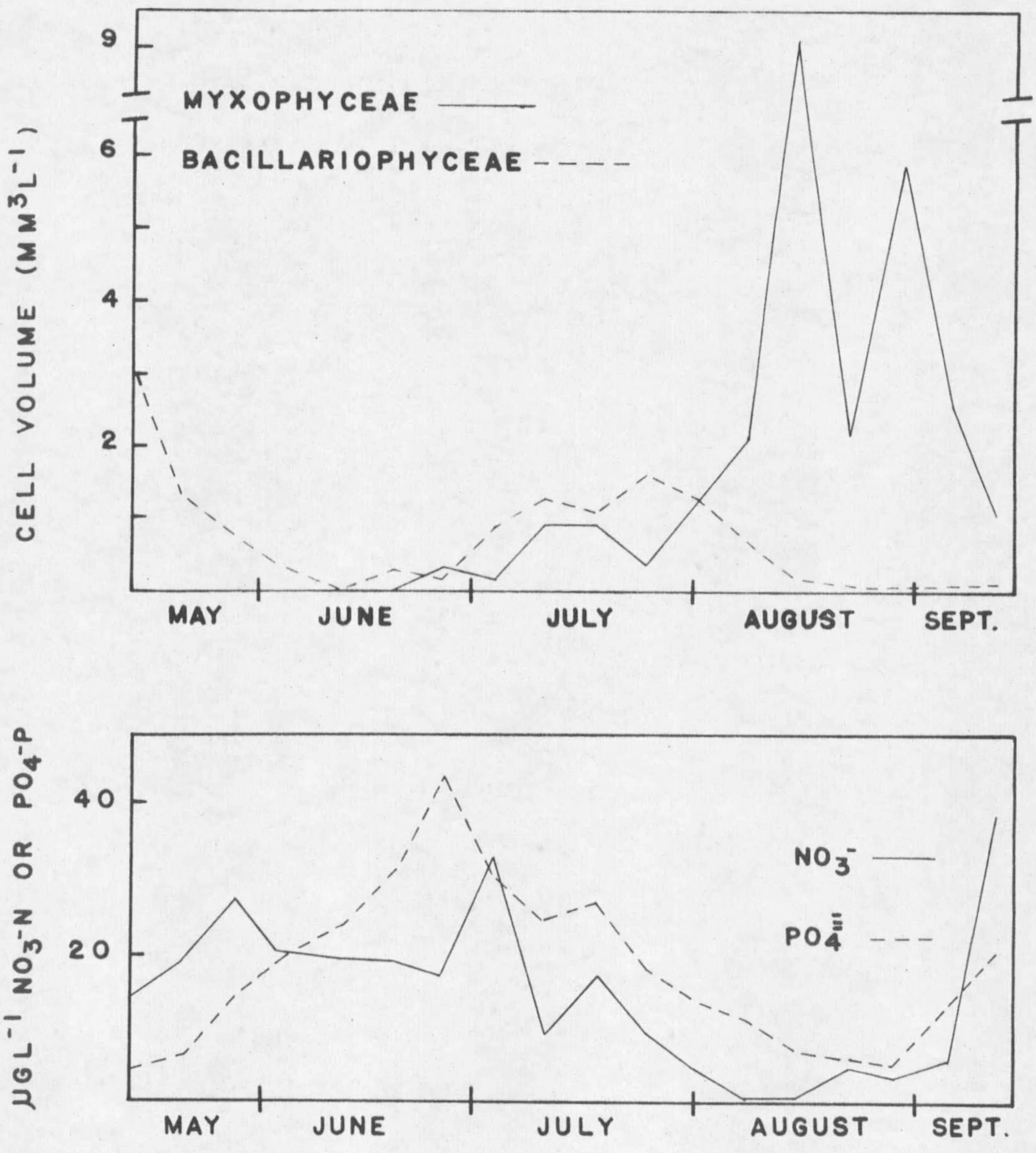

Figure 14. Average seasonal euphotic zone concentrations of nitrate and ortho-phosphorus together with average standing crops of Bacillariophyceae and Myxophyceae during 1972.

Each year euphotic zone concentrations of nitrate became low to undetectable at all stations during late July and early August. At that same time ortho-phosphorus was low to undetectable. The increase in diatom standing crops during late July suggests a luxury consumption or internal storage of nutrients within the cells (Caperon and Meyer 1972 and Shapiro 1970) earlier when the nutrients were more abundant. This was especially apparent during 1971. The bloom of blue-green algae which followed nitrate depletion could be explained by nitrogen fixation. *Aphanizomenon flos-aquae*, which was by far the most abundant alga in Canyon Ferry, has been shown to be capable of fixing molecular nitrogen (Horne and Goldman 1972, Horne et al. 1972, and Brezonik, 1972). Rigler (1956 and 1964) and Lean (1973) worked on the dynamics of phosphorus in lake waters. Their findings suggest that during the summer, bloom-forming algae are extremely efficient at taking up phosphorus from dilute solutions (Hutchinson 1973). Consequently, these algae can compete favorably with the less efficient forms, especially if the former can also fix their own molecular nitrogen. This appeared to be the situation in Canyon Ferry.

The greater amount of inorganic nitrogen observed in the outflow as compared to the inflow each year could be explained by nitrogen fixation of *Aphanizomenon flos-aquae* during late summer after nitrate had been depleted. Release of the fixed nitrogen to the lake would, however, have been delayed until the algal cells had decomposed and nitrification had occurred. This would have taken place to a large degree in the sediments.

It was mentioned earlier (page 21) that the difference in hydrologic regimes between 1971 and 1972 could have been an important factor regulating the amount of nitrogen recycled each year. During spring drawdown in 1972, the area of reservoir bottom exposed to the atmosphere was 30% less than in 1971. Correspondingly, the discharge of nitrate during 1972 was only 63% of that discharged during 1971 and the average nitrate storage in the reservoir during 1972 was only 70% of that observed during 1971.

Sedimented plankton could have been more readily decomposed and nitrification could have been more rapid when the sediments were exposed to the atmosphere than when submerged. The larger load of nitrate found in the outflow during 1971 as compared to 1972 was probably associated with greater drawdown during 1971. Consequently, the extent of drawdown could have been an important factor in the relative amount of nitrogen recycled in the reservoir each year.

Figure 15 shows the seasonal storage of ammonia and nitrate in Canyon Ferry. Maximum storage of ammonia, which occurred during June each year, appeared to be associated with submerging that portion of reservoir bottom that had been previously exposed to the atmosphere because of spring drawdown. A relatively large amount of ammonia could have been released into the water as a result of flooding the decomposed

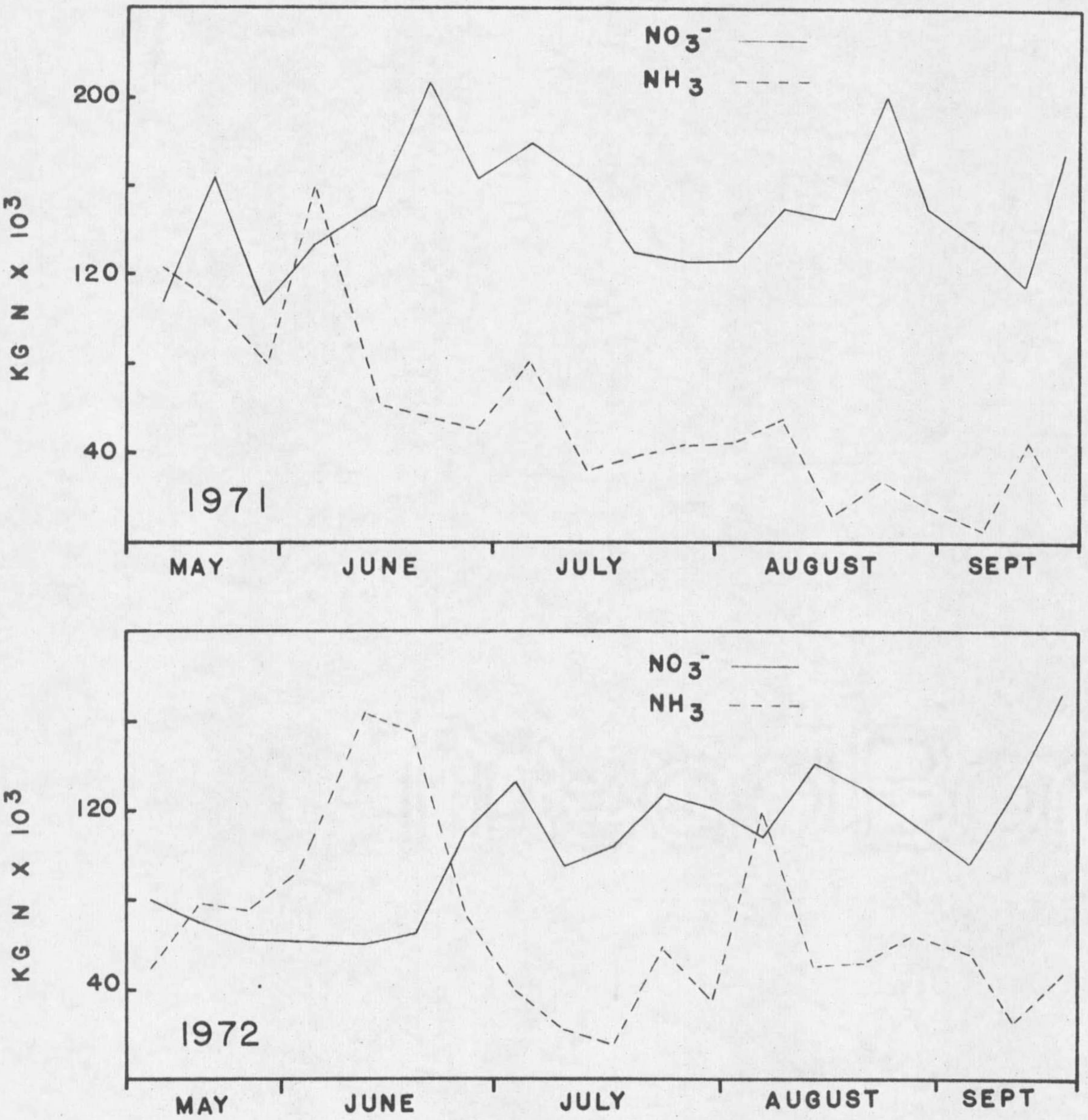

Figure 15. Seasonal storage of nitrate and ammonia in Canyon Ferry Reservoir during the regular sampling seasons.

and ammonified organic matter in the sediment. Corresponding to the subsequent drop in ammonia was an increase in nitrate, indicating that nitrification was occurring. For the remainder of the season, nitrate storage remained relatively high.

Seasonal storage of ortho-phosphorus is depicted in Figure 16. Maximum ortho-phosphorus storage was observed on 5 July 1971 and 26 June 1972. These maxima appeared to be related primarily to regeneration of ortho-phosphorus within the reservoir in addition to somewhat higher loads in the inflow than in the outflow. The subsequent decrease in ortho-phosphorus was probably due to uptake by phytoplankton (see also Figures 13 and 14).

As a result of work on several Wisconsin lakes, Sawyer (1947 and 1952) suggested that critical threshold concentrations of 300 $\mu g \cdot L^{-1}$ inorganic nitrogen and 10 $\mu g \cdot L^{-1}$ inorganic phosphorus at the beginning of an active growing season could be expected to produce algal blooms of nuisance proportions. Vollenweider's (1970) statistical analysis on data collected by Thomas (1953) showed that the threshold concentrations suggested by Sawyer (1947 and 1952) were a good general guideline.

Inorganic nitrogen in Canyon Ferry was below the critical threshold values; however, inorganic phosphorus was in excess of the threshold concentrations. Algal blooms could have been expected because of the relatively high phosphorus concentrations, in addition to the fact that the dominant species *(Aphanizomenon flos-aquae)* in Canyon Ferry was

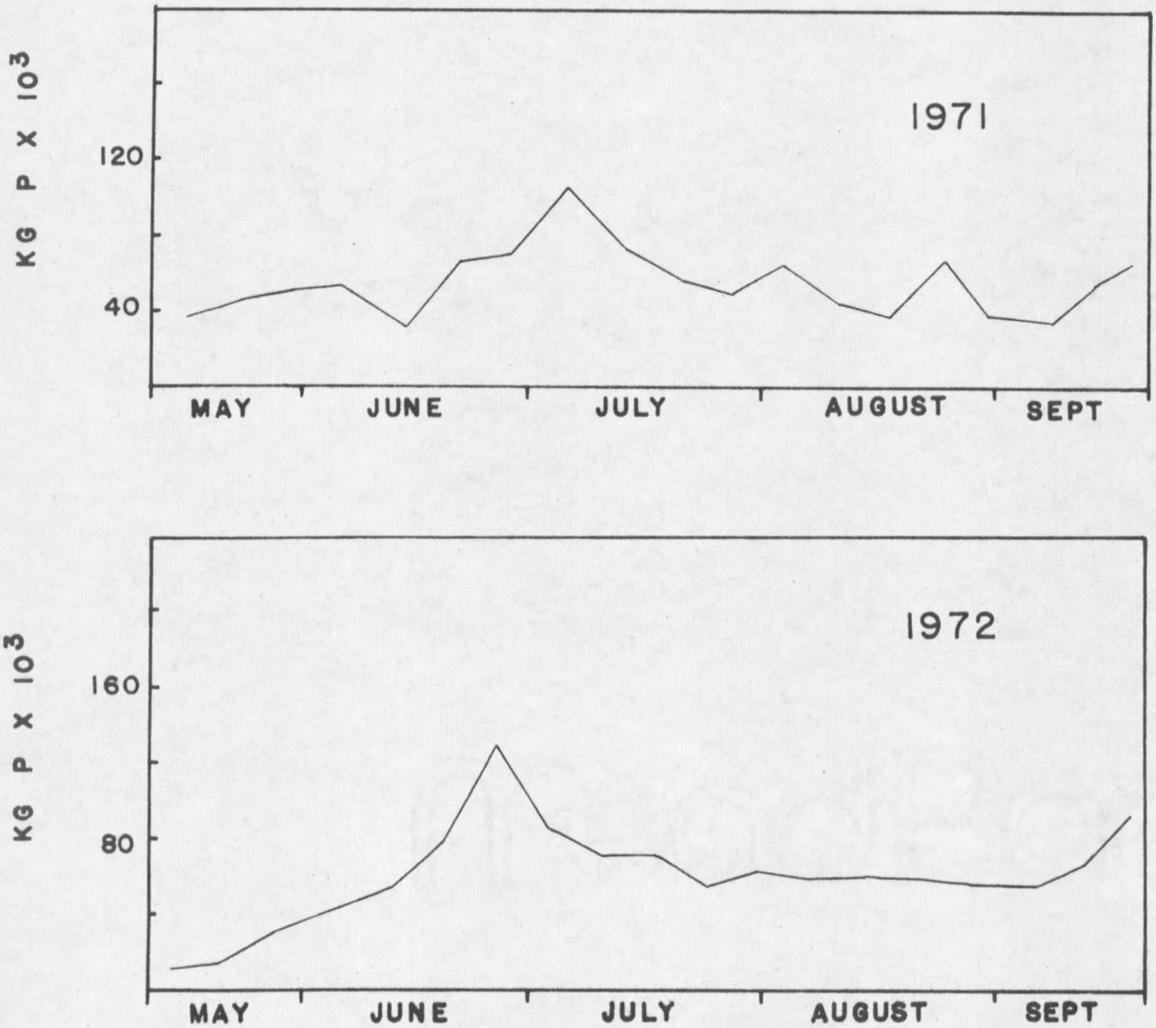

Figure 16. Seasonal storage of ortho-phosphorus in Canyon Ferry Reservoir during the regular sampling seasons.

capable of fixing nitrogen.

Vollenweider (1970) suggested that annual surface loading of nutrients with respect to mean depth was a better indication of the trophic state of lakes than the concentration of nutrients at vernal overturn. The importance of mean depth to the productivity of lakes has been discussed by Rawson (1955 and 1960).

According to Vollenweider's (1970) model, Canyon Ferry would be classified as mesotrophic on the basis of inorganic nitrogen loading and highly eutrophic on the basis of ortho-phosphorus (Figure 17). With respect to ortho-phosphorus loading, Canyon Ferry appeared to be nearly as eutrophic as Lake Erie (Campbell 1969). However, Vollenweider's model was based on data from natural lakes which have surface outflows and consequently tend to act as phosphorus traps. Conversely, many reservoirs such as Canyon Ferry have deep-water outflows and tend to discharge much of the nutrient load downstream. During this study far more inorganic nitrogen and ortho-phosphorus were discharged from Canyon Ferry than entered the reservoir. Although there was a net accumulation of total phosphorus during each May-September sampling period, there was no net accumulation of total phosphorus when the phosphorus budget was determined for nearly a complete year (June, 1972 through April, 1973). This evidence indicates that Canyon Ferry does not fit Vollenweider's model. Consequently, caution must be exercised when attempting to apply his classification to reservoirs which differ

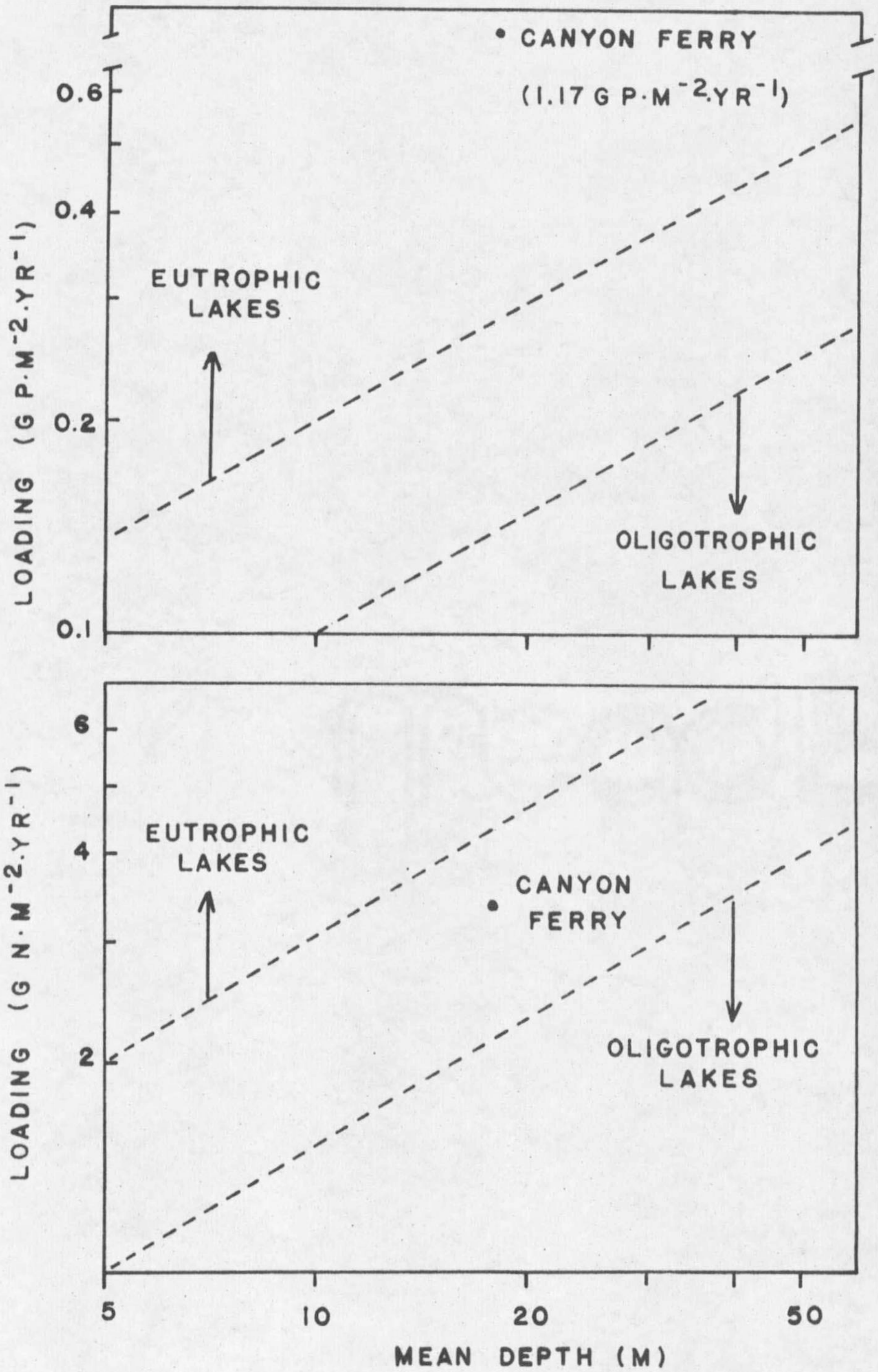

Figure 17. Vollenweider's (1970) model for the trophic classification of lakes based on annual specific surface loading of orthophosphorus and inorganic nitrogen as a function of mean depth.

markedly from natural lakes.

Phytoplankton Standing Crops, Chlorophyll *a*, and Primary Production

Phytoplankton taxonomic composition. The phytoplankton in Canyon Ferry were represented by five classes of algae: Bacillariophyceae (diatoms), Chlorophyceae (green algae), Cryptophyceae (cryptomonads), Dinophyceae (dinoflagellates), and Myxophyceae (blue-green algae). Within these, 65 species were identified, 56 in 1971 and 59 in 1972 (Table 18).

The 33 species of Class Bacillariophyceae found in the reservoir comprised 49% of the total cell volume in 1971 and 34% in 1972. Major species in 1971 were *Fragilaria crotonensis*, *Stephanodiscus niagarae*, and *Melosira granulata* which ranked second, third, and fourth, respectively, on a cell volume basis. These three species, in addition to *Diatoma elongatum*, were also prominent in 1972. *F. crotonensis* and *S. niagarae* appeared in more than 80% of the samples taken.

Chlorophyceae were represented by 19 species but were never a major component of the algal flora in Canyon Ferry. They contributed only 4% of the cell volume in 1971 and 2% in 1972. *Ankistrodesmus* spp. were observed in 55% of the samples and were the most frequently encountered green algae.

Only three species of the Class Cryptophyceae were found with *Rhodomonas lacustris* occurring in 78% of the samples and *Cryptomonas*

Table 18. Euphotic zone phytoplankton species composition for all stations in Canyon Ferry Reservoir.

TAXON	1971	1972
Division: CRYSOPHYTA (Yellow-Green Algae)		
Class: Bacillariophyceae (Diatoms)		
Achnanthes spp. Bory.	x	x
Asterionella formosa Hassal.	x	x
Cocconeis spp. Ehr.	x	x
Cyclotella spp. Kutz.	x	x
Cymatopleura solea (Breb.) W. Smith.		x
Cymbella affinis Kutz.	x	x
Denticula elegans Kutz.	x	x
Diatoma elongatum Agardh.	x	x
Diatoma hiemale (Roth) Heib.	x	x
Diatoma vulgare Bory.	x	x
Epithemia sorex Kutz.	x	x
Epithemia turgida (Ehr.) Kutz.		x
Eunotia sp. Ehr.	x	x
Fragilaria capucina Desmazieres.	x	
Fragilaria construens (Ehr.) Grun.	x	x
Fragilaria crotonensis Kitton.	x	x
Gomphonema spp. Agardh.	x	x
Hannae arcus (Ehr.) Patr.	x	x
Melosira granulata (Ehr.) Ralfs.	x	x
Melosira italica (Ehr.) Kutz.	x	x
Navicula spp. Bory.	x	x
Nitzschia dissipata (Kutz.) Grunow.	x	x
Nitzschia linearis W. Smith.	x	x
Rhoicosphenia curvata (Kutz.) Grunow.	x	x
Rhopalodia sp. O. muller.	x	
Stephanodiscus astraea (Ehr.) Grun.	x	x
Stephanodiscus niagarae Ehr.	x	x
Surirella ovalis de Brebisson.		
Surirella ovata Kutz.		x
Synedra acus Kutz.	x	x
Synedra pulchella Ralfs en Kutz.	x	x
Synedra ulna (Nitzsch.) Ehr.	x	x
Synedra vaucheria (Kutz.) Kutz.	x	x

Table 18 Continued.

TAXON	1971	1972
Division: CHLOROPHYTA (Green-Algae)		
Class: Chlorophyceae		
Actinastrum hantzschii Lagerheim.		x
Ankistrodesmus braunii (Naeg.) Brunnthaler.		x
Ankistrodesmus convolutus Corda.	x	x
Ankistrodesmus falcatus (Corda) Ralfs.	x	x
Ankistrodesmus fractus (West & West) Brunnthaler.		x
Botryococcus braunii Kutz.		x
Carteria sp. Diesing.	x	x
Characium sp. A. Braun.	x	x
Chlamydomonas sp. Ehr.	x	x
Chlorella spp. Beijernick.	x	x
Closterium sp. Nitzsch.	x	x
Eudorina elegans Ehr.	x	x
Pandorina morum (Muell.) Bory.	x	
Pediastrum biradiatum Meyen.		x
Pediastrum duplex Meyen.	x	x
Scenedesmus quadricauda (Turp.) de Brebisson.	x	x
Schroederia setigera (Schroed.) Lemmermann.	x	x
Selenastrum sp. Reinsch.	x	x
Sphaerocystis schroeteri Chodat.	x	x
Staurastrum paradoxum Meyen.	x	x
Division: CYANOPHYTA (Blue-Green Algae)		
Class: Myxophyceae		
Anabaena flos-aquae (Lyngb.) de Brebisson.	x	x
Aphanizomenon flos-aquae (L.) Ralfs.	x	x
Aphanothece sp. Naegeli.		x
Coelosphaerium naegelianum Unger.	x	x
Lyngbya biregi Smith.	x	
Microcystis aeruginosa Kutz.	x	x
Oscillatoria sp. Vaucher.	x	

Table 18 Continued.

TAXON	1971	1972
Division: PYRRHOPHYTA (Dinoflagellates)		
Class: Dinophyceae		
Ceratium hirundinella (O. F. Muell.) Dujardin.	x	x
Peridinium sp. Ehr.	x	
Division: CRYPTOPHYTA (Blue and Red Flagellates)		
Class: Cryptophyceae		
Cryptomonas erosa Ehr.	x	x
Cryptomonas ovata Ehr.	x	x
Rhodomonas lacustris Pasch. & Ruttn.	x	x

ovata occurring in 74%. Although appearing frequently, the cryptomonads comprised less than 5% of the total cell volume.

Class Dinophyceae comprised only 2% of the cell volume each year and was represented by two species. *Ceratium hirundinella*, the only important dinoflagellate, ranked sixth and eighth on a cell volume basis during the successive years and appeared in 53% of the samples.

Myxophyceae was one of the two most important classes of algae in Canyon Ferry. *Aphanizomenon flos-aquae* was the most abundant species in the reservoir and comprised 41% of the total cell volume in 1971 and 54% in 1972. *Coelosphaerium naegelianum* was important during 1971 and *Microcystis aeruginosa* was an important species both years.

Table 19 depicts the ranks of the major phytoplankton taxa according to cell volume and Table 20 depicts the ranks of the major phytoplankton taxa according to frequency of occurrence (%). The frequency of occurrence of a particular species is defined as the percentage of samples within which any particular species was found.

Horizontal distribution. Yearly average standing crops on a ($mm^3 \cdot L^{-1}$) basis exhibited similar horizontal distributions each year. Figure 18 indicates that the upper end of the reservoir had higher phytoplankton densities than the lower end. Data from Stations 1 and 2 were combined to represent phytoplankton standing crops of the lower end of Canyon Ferry and data from Stations 3 and 4 were combined to represent the upper end. A paired t-test was then performed to

Table 19. Major phytoplankton taxa in the euphotic zone of Canyon Ferry Reservoir ranked according to average cell volumes ($mm^3 \cdot L^{-1}$). Data are based on samples from all stations during 1971 and 1972.

	Rank	Taxon	Cell Volume
	1	*Aphanizomenon flos-aquae*	0.97
	2	*Fragilaria crotonensis*	0.48
	3	*Stephanodiscus niagarae*	0.32
	4	*Melosira granulata*	0.19
1	5	Microplankton	0.07
	6	*Ceratium hirundinella*	0.05
9		*Stephanodiscus astraea*	0.05
		Cryptomonas ovata	0.05
7	7	*Melosira italica*	0.04
	8	*Navicula* spp.	0.02
1	9	*Diatoma vulgare*	0.01
		Coelosphaerium naegelianum	0.01
		Lynbgya birgei	0.01
		Microcystis aeruginosa	0.01
		Rhodomonas lacustris	0.01
		Synedra spp.	0.01
	1	*Aphanizomenon flos-aquae*	1.14
	2	*Fragilaria crotonensis*	0.19
	3	*Diatoma elongatum*	0.13
	4	*Melosira granulata*	0.12
1	5	*Stephanodiscus niagarae*	0.10
	6	*Cryptomonas ovata*	0.07
9	7	*Asterionella formosa*	0.05
		Microcystis aeruginosa	0.05
7	8	*Stephanodiscus astraea*	0.04
		Ceratium hirundinella	0.04
2	9	*Rhodomonas lacustris*	0.03
	10	*Synedra* spp.	0.02
		Microplankton	0.02
		Surirella ovalis	0.02
	11	*Melosira italica*	0.01

Table 20. Major phytoplankton taxa in the euphotic zone of Canyon Ferry Reservoir ranked according to their frequency of occurrence (%). The data are based on samples from all stations during 1971 and 1972.

	Rank	Taxon	Frequency of Occurrence
	1	*Stephanodiscus niagarae*	94
	2	*Fragilaria crotonensis*	90
	3	*Melosira granulata*	84
	4	*Cryptomonas ovata*	71
	5	*Rhodomonas lacustris*	66
1	6	*Aphanizomenon flos-aquae*	65
	7	*Ankistrodesmus* spp.	59
9	8	*Staurastrum paradoxum*	53
	9	*Asterionella formosa*	52
7	10	*Ceratium hirundinella*	49
		Melosira italica	49
1	11	*Navicula* spp.	41
	12	*Cocconeis* spp.	32
	13	*Synedra* spp.	31
	14	*Microcystis aeruginosa*	29
		Stephanodiscus astraea	29
	15	*Diatoma elongatum*	28
	1	*Rhodomonas lacustris*	89
	2	*Cryptomonas ovata*	77
		Fragilaria crotonensis	77
	3	*Stephanodiscus niagarae*	70
	4	*Aphanizomenon flos-aquae*	64
	5	*Ceratium hirundinella*	57
1	6	*Melosira granulata*	54
	7	*Ankistrodesmus* spp.	51
9	8	*Asterionella formosa*	49
		Staurastrum paradoxum	49
7	9	*Microcystis aeruginosa*	41
	10	*Synedra* spp.	37
2	11	*Cyclotella* spp.	36
		Stephanodiscus astraea	36
	12	*Coelosphaerium naegelianum*	31
		Navicula sp.	31
	13	*Cymbella affinis*	29
	14	*Melosira italica*	24

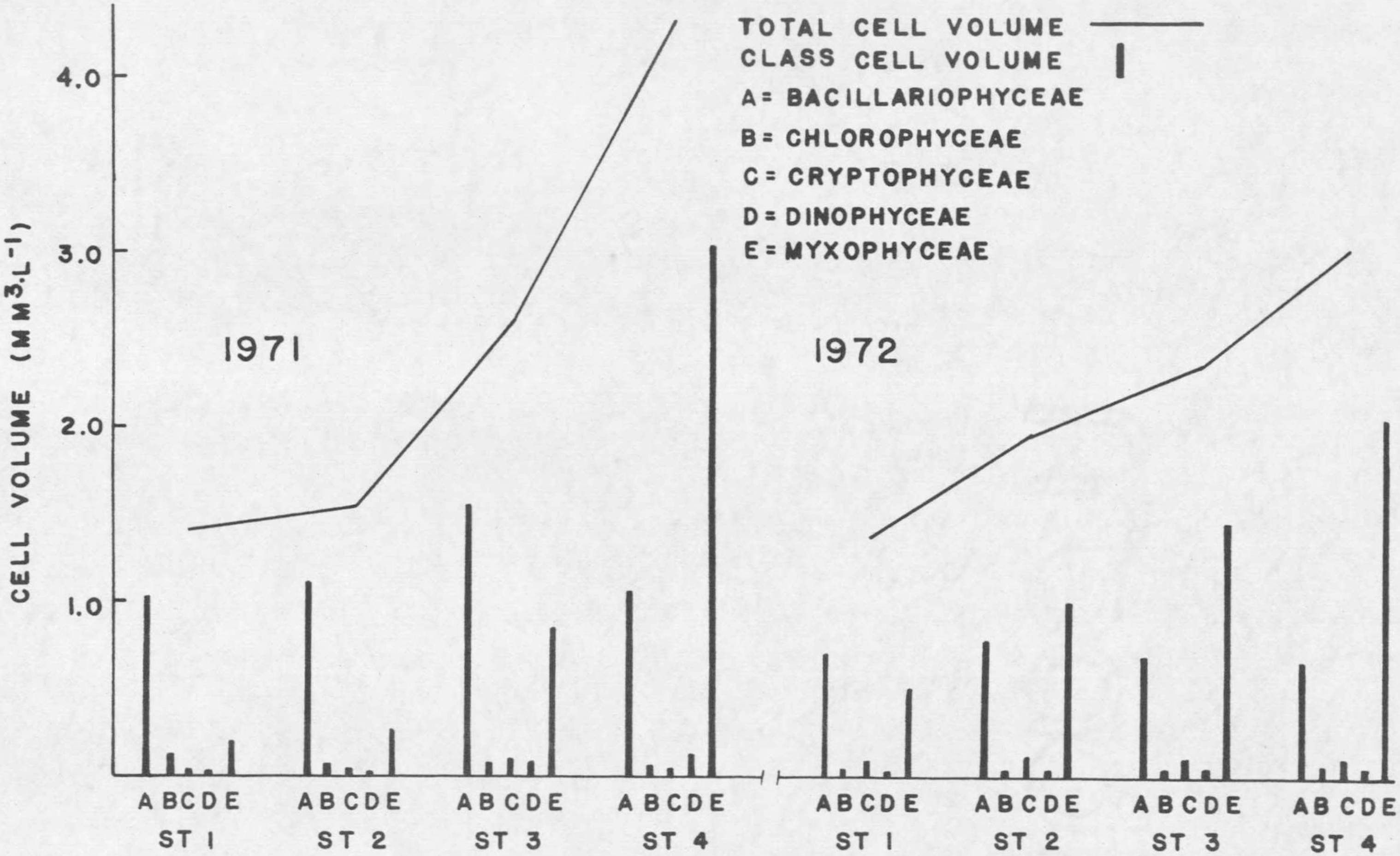

Figure 18. Horizontal distribution of yearly average euphotic zone phytoplankton standing crops presented on a volume basis ($mm^3 \cdot L^{-1}$). Both total and class cell volumes are expressed.

determine whether there were significant differences between the upper and lower regions of the reservoir. The results were $p = 0.01$ in 1971 and $p = 0.08$ in 1972. This evidence supports the trend shown in Figure 18.

When standing crops are computed on an areal basis ($mm^3 \cdot m^{-2}$), different horizontal distributions of phytoplankton become apparent (Figure 19). On an areal basis there was no significant difference ($p = 0.38$) between the upper and lower reaches of the reservoir in 1971, whereas there was a significant difference ($p = 0.03$) in 1972. This indicates that on an areal basis, the lower end of Canyon Ferry had larger standing crops than the upper end during 1972.

The apparent contradiction between standing crops expressed on volume ($mm^3 \cdot L^{-1}$) and areal ($mm^3 \cdot m^{-2}$) bases could be explained by the differences between euphotic zone depths of the various stations. In other words, $mm^3 \cdot L^{-1}$ gives the average concentration per liter of euphotic zone volume, whereas $mm^3 \cdot m^{-2}$ compensates for depth and gives an estimate of the absolute phytoplankton cell volume under a m^2 of euphotic zone surface. Later discussions will be restricted to $mm^3 \cdot L^{-1}$ to facilitate comparison with the earlier study on Canyon Ferry by Wright (1959, 1965, and unpublished data).

Highest average phytoplankton densities were encountered at Station 4 each year. They were 4.33 $mm^3 \cdot L^{-1}$ in 1971 and 3.00 $mm^3 \cdot L^{-1}$ in 1972. Because of large standing crops of *Aphanizomenon flos-aquae*,

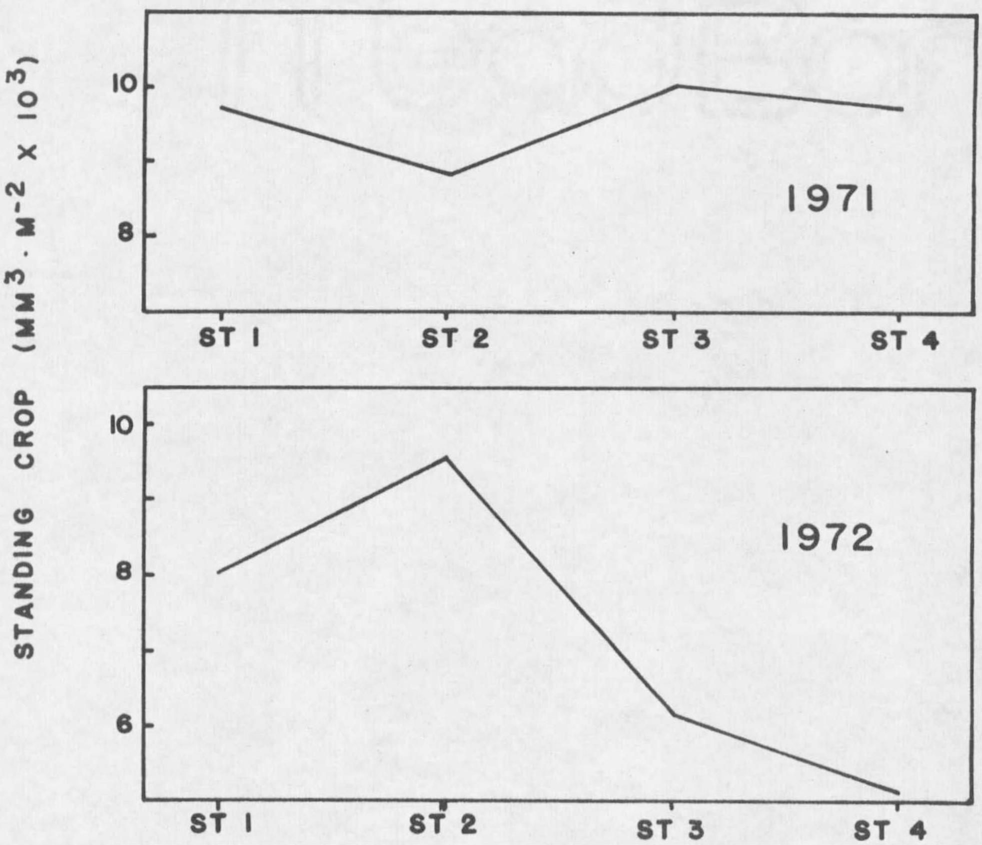

Figure 19. Horizontal distribution of yearly average euphotic zone phytoplankton standing crops presented on an areal basis ($mm^3 \cdot m^{-2}$).

blue-green algae were the predominant phytoplankton at this station. Diatoms were the second most abundant class of algae each year.

Diatoms, followed by blue-green algae, comprised most of the large standing crop observed at Station 3 during 1971. Conversely, blue-green algae, followed by the diatoms, were the dominant phytoplankton in 1972.

Relatively low standing crops were observed at Station 2 each year. The diatoms were by far the most abundant phytoplankton in 1971 while both the diatoms and blue-greens were prevalent in 1972.

Diatoms were the predominant class of phytoplankton at Station 1 each year; however, in 1972 the blue-green algae were also relatively abundant. Table 21 compares average phytoplankton standing crops at Station 1 during 1957 and 1958 to those observed during 1971 and 1972. The data for 1957 and 1958 were obtained from Wright (1965 and unpublished data). Yearly average standing crops were 5.90 $mm^3 \cdot L^{-1}$ in 1957 and 3.04 $mm^3 \cdot L^{-1}$ in 1958 as compared with 1.41 and 1.37 $mm^3 \cdot L^{-1}$ during 1971 and 1972, respectively. Blue-green algae were the most abundant phytoplankton in 1957, whereas the diatoms were dominant in 1958. With regard to average total standing crops, Station 1 during the 1957-1958 study was more similar to Station 4 than Station 1 during the 1971-1972 study. On 22 July 1957 the blue-green algae were dense enough to limit the euphotic zone depth to less than 0.3 m (1 ft). During the present study, the euphotic zone depth at Station 1 averaged more than 6 m and

Table 21. A comparison of the euphotic zone phytoplankton standing crops ($mm^3 \cdot L^{-1}$) at Station 1 in Canyon Ferry during 1957-1958 with those during 1971-1972.

	1957		1958		1971		1972	
	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Bacillariophyceae	1.85	6.19	1.98	7.50	1.03	4.81	0.75	2.62
Chlorophyceae	0.07	0.12	0.08	0.94	0.13	1.69	0.03	0.10
Cryptophyceae	0.76	2.63	0.44	1.52	0.05	0.15	0.07	0.40
Dinophyceae	0.06	0.22	0	0.02	0.01	0.07	0.02	0.12
Myxophyceae	3.13	29.21	0.54	4.61	0.19	1.02	0.50	5.23
TOTAL	5.90	29.75	3.04	8.02	1.41	4.99	1.37	5.53

was never less than 3 m. *A. flos-aquae*, however, was dense enough at times during the summer to limit the euphotic zone depth to less than 1 m at Station 4. On the basis of total phytoplankton standing crops at Station 1, Canyon Ferry appeared to be substantially more productive during 1957-1958 than in 1971-1972. This phenomenon might have been expected because inundation normally releases organic and inorganic materials from the bottom lands. As a result, reservoirs have a high initial productive potential. Subsequently, they tend to experience a decline in production and never seem to regain their initial production levels (Carlander et al. 1963 and Neel 1963).

<u>Seasonal distribution and community succession</u>. Ice cover on Canyon Ferry usually broke up during April, but sampling during this study did not begin until mid-May. Wright, however, began sampling during early April in 1957 and mid-April in 1958. His findings showed that the main spring diatom peak occurred during late April in 1957 and early May in 1958 (Wright unpublished data). Hence, the spring diatom peak probably was not observed during the regular sampling periods in 1971 and 1972.

Monthly average standing crops are depicted in Figure 20 and relative standing crops of five major phytoplankton taxa are shown in Figures 21 and 22. *S. astraea*, *F. crotonensis*, and *M. italica* were the main phytoplankters when sampling began in 1971. Microplankton were also abundant early in the season. Although *C. ovata* attained its

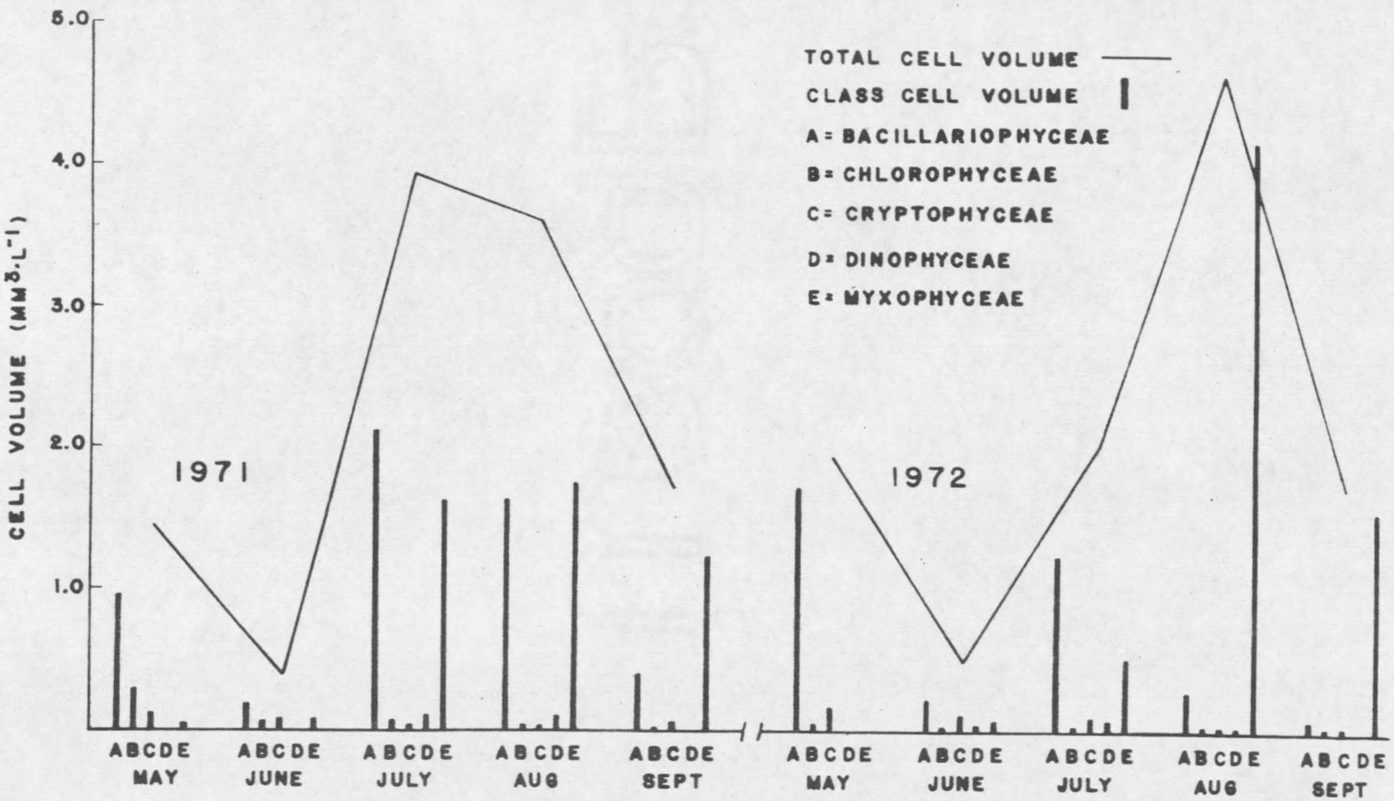

Figure 20. Average monthly standing crops of euphotic zone phytoplankton based on samples taken from the entire reservoir during 1971 and 1972.

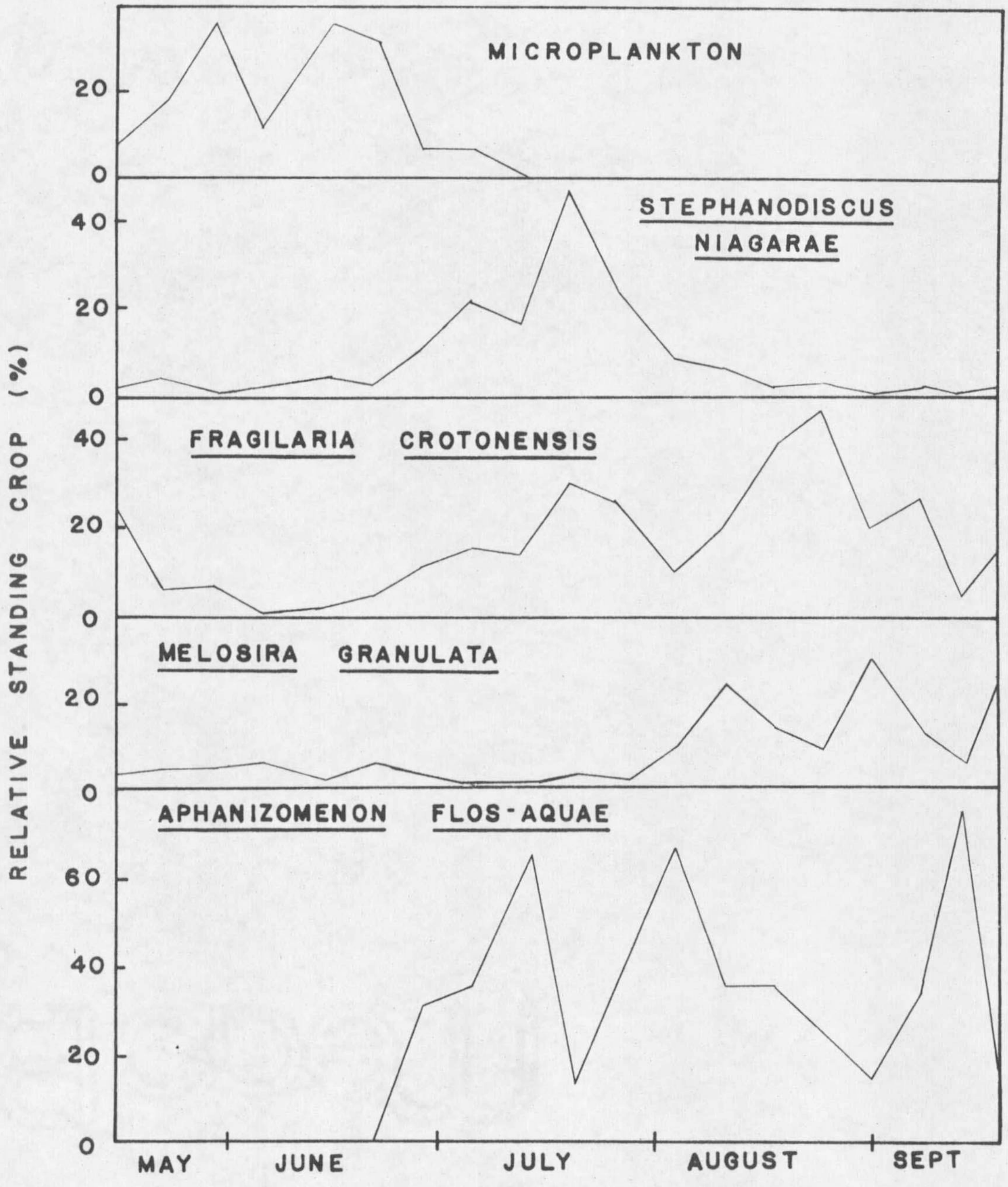

Figure 21. Relative standing crops of five major phytoplankton taxa in the euphotic zone of Canyon Ferry Reservoir. The data are based on weekly averages of samples taken from the entire reservoir during 1971.

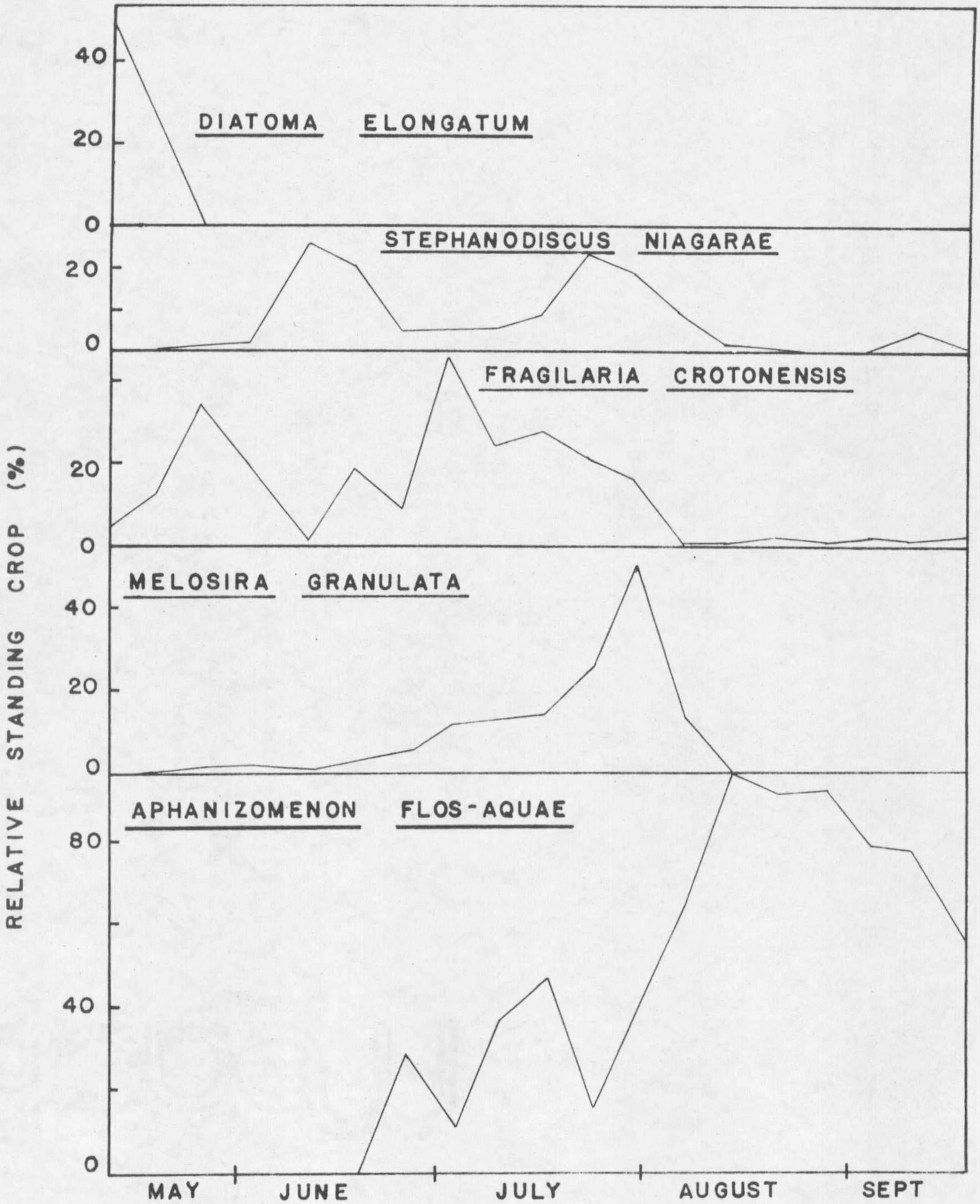

Figure 22. Relative standing crops of five major phytoplankton taxa in the euphotic zone of Canyon Ferry Reservoir. The data are based on weekly averages of samples taken from the entire reservoir during 1972.

largest absolute cell volumes during May, it reached its largest relative standing crop in June when total standing crop was at a seasonal low. Phytoplankton densities were high during July as a result of large standing crops of *S. niagarae*, *F. crotonensis*, and *A. flos-aquae*. Large phytoplankton populations also occurred in August and were composed primarily of *A. flos-aquae*, *F. crotonensis*, and *M. granulata*. Standing crops dropped markedly in September and were dominated by *A. flos-aquae*.

Diatoma elongatum was the most abundant phytoplankter at the beginning of the 1972 season with *Asterionella formosa*, *S. astraea*, and *F. crotonensis* also prominent. Again, phytoplankton densities were low in June when *S. niagarae*, *C. ovata*, and Ceratium *hirundinella* reached their highest relative standing crops. *F. crotonensis* and *M. granulata* accounted for most of the July phytoplankton while *A. flos-aquae* was dominant for the remainder of the sampling season.

Similar seasonal patterns were demonstrated by Wright at Station 1 during 1957 and 1958 (Wright 1965 and unpublished data). *Cyclotella* was the main phytoplankter during the spring diatom peak and was accompanied by substantial quantities of *Fragilaria* and lesser amounts of *Asterionella* and *Stephanodiscus*. *Cryptomonas* and *Rhodomonas* reached their highest cell volumes during mid-May of 1957 and mid-June of 1958. *Fragilaria*, accompanied by smaller quantities of *Melosira*, accounted for the majority of the total standing crop through much of July.

Aphanizomenon increased from approximately 1 $mm^3 \cdot L^{-1}$ on 17 July 1957 to over 29 $mm^3 \cdot L^{-1}$ on 22 July 1957. *Microcystis* also became important during the late summer. The main difference between 1957 and 1958 was that blue-green algae dominated the phytoplankton on only two occasions in 1958. Another difference was that during 1958 *Microcystis* was the major blue-green alga while *Aphanizomenon* never developed as a major species.

Each year the vernal diatom peak in Canyon Ferry occurred when light intensities were increasing and nutrients were abundant. A decline in phytoplankton population occurred in June but did not appear to be due to nutrient limitation since inorganic nitrogen and orthophosphorus were abundant at that time (Figures 13 and 14). However, coincidental with the decrease in phytoplankton were increases in the *Cyclops* and *Daphnia* populations (Martin in review). The inference is that the diatoms, along with the cryptomonads and small green algae, were being grazed by zooplankton. A similar phenomenon was observed in Canyon Ferry by Wright (1965). Edmondson (1962) and Richman (1966) have also noted decreases in phytoplankton standing crops as a result of zooplankton grazing. After the zooplankton declined, the phytoplankton, mainly diatoms and blue-greens, increased significantly. During 1971 the diatoms sustained relatively high standing crops through August, whereas in 1971 they declined after July.

Blue-green algae, which are thought to thrive with warmth and high illumination, became abundant when the surface temperature reached 17°C. Bloom conditions were observed when the temperature approached 20°C. In addition to their ability to fix nitrogen, blue-greens have a competitive advantage over other algae due to efficient phosphorus uptake mechanisms (Hutchinson 1973). They also appear to have a more efficient mechanism for utilizing the bicarbonate ion when the concentration of free carbon dioxide is low. At least they are limited less than other algae under low carbon dioxide/high bicarbonate conditions (Hutchinson 1973). In support of this reasoning, Shapiro (1973) demonstrated a shift in dominance from blue-green algae to green algae by lowering the pH and/or adding carbon dioxide to mixed cultures of lake phytoplankton. The pH in Canyon Ferry ranged from 8.3-8.7 when the largest populations of blue-greens occurred. Hence, carbon dioxide was low and bicarbonate was abundant.

Perhaps an important factor allowing the blue-green algae to dominate the phytoplankton during the mid-late summer was their relative freedom from grazing pressure exerted by zooplankton. Hutchinson (1973) and Lund (1969) noted that because of their shape and gelatinous texture, blue-green algae are relatively unaffected by grazing crustaceans. Diatoms, cryptomonads, and other small flagellates are, however, readily eaten and digested. Conversely, Knutson (1970) indicated that *Aphanizomenon* appeared to be an important food source for *Daphnia* during the summer and fall in Lake Ashtabula, North Dakota.

Blue-green algae can also regulate their buoyancy which allows them to form dense surface layers (Fogg 1965). The resulting shading effect on less buoyant algae could be another competitive advantage.

Myxophycean algae, therefore, seem to possess many adaptations which enable them to out-compete other algae during the mid-late summer in lakes such as Canyon Ferry. Other factors regulating seasonal succession of phytoplankton have been extensively reviewed by Rodhe (1948), Lund (1965), Fogg (1965), and Hutchinson (1967).

Chlorophyll *a* and cell volume relationships. A consistent relationship between phytoplankton cell volume and chlorophyll *a* concentration was observed during this study. This should be a reasonable observation since chlorophyll molecules are primary components of the photosynthetic units which capture solar energy in the light reaction of photosynthesis. High correlations were also observed by Martin (1967), Brylinsky and Mann (1973), and Wright and Soltero (1973). The only time during this study that the correlation between chlorophyll concentration and phytoplankton cell volume was low occurred in June, 1971. At this time cell volume was lower than indicated from the chlorophyll *a* concentration (Figures 23 and 24). Pheophytin *a* has an absorption peak in the same portion of the visible spectrum as chlorophyll *a* (EPA 1973). Therefore, the presence of pheophytins in the fecal material and remains of large zooplankton populations occurring at this time could have explained the low correlation.

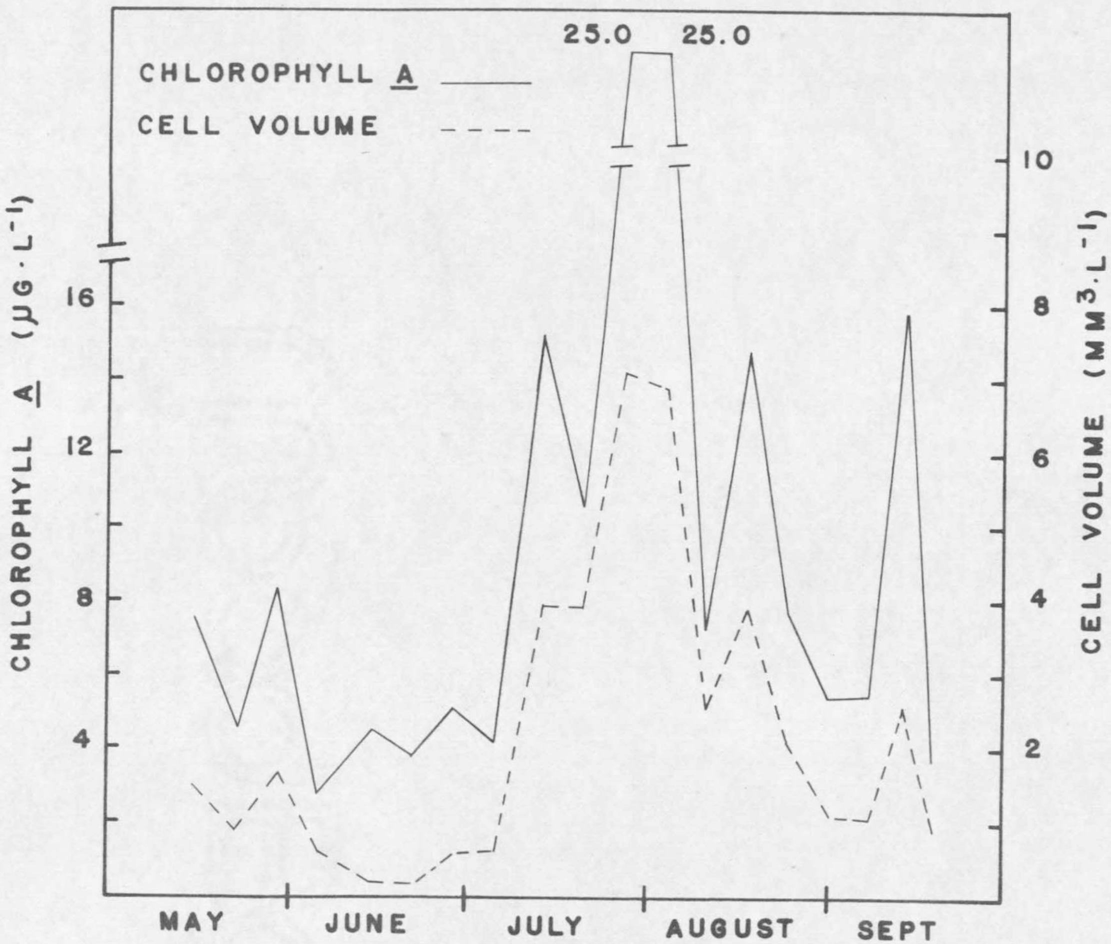

Figure 23. Seasonal relationship between average chlorophyll *a* concentration and average euphotic zone phytoplankton cell volume. The data are based on weekly samples taken from the entire reservoir during 1971.

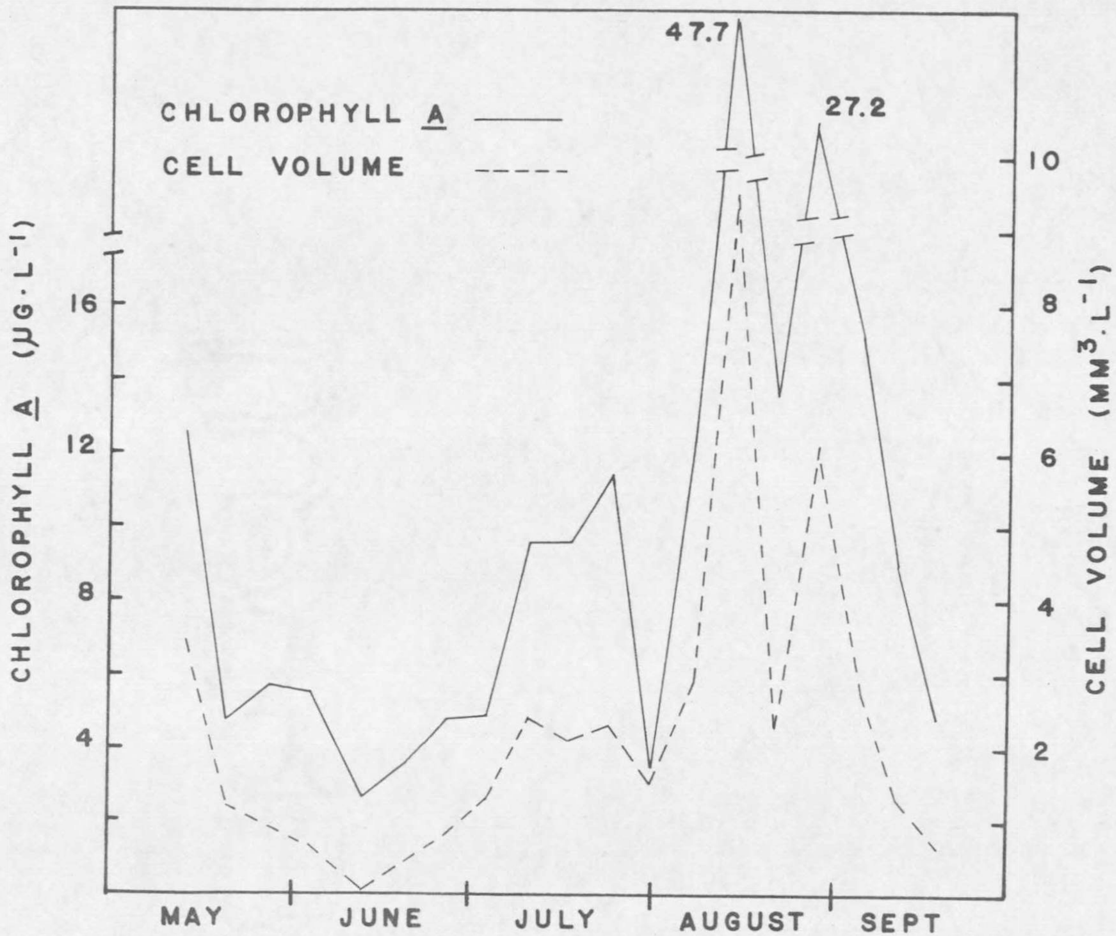

Figure 24. Seasonal relationship between average chlorophyll *a* concentration and average euphotic zone phytoplankton cell volume. The data are based on weekly samples taken from the entire reservoir during 1972.

Glooschenko et al. (1972) showed a high correlation between pheo-pigment content and zooplankton abundance. They indicated that this was probably a causal relationship because the passage of phytoplankton cells through the acidic digestive tract of zooplankton could convert the chlorophyll to pheo-pigments.

In Canyon Ferry the correlation coefficient (r) between average phytoplankton cell volume and average chlorophyll *a* concentration on each sampling date was $r = 0.95$ ($p < 0.01$). A similar correlation was found by Brylinsky and Mann (1973). A simple linear regression between average phytoplankton cell volume and average chlorophyll *a* concentration was performed and the following regression equation was determined:

$$\text{Chlorophyll } a \ (\mu g \cdot L^{-1}) = 4.07 \text{ C.V. } (mm^3 \cdot L^{-1}) + 0.70$$

This indicated that a change of 1.0 $mm^3 \cdot L^{-1}$ in cell volume was equivalent to a change of 4.07 μg chlorophyll $a \cdot L^{-1}$ (Figure 25). Similarly, Wright (1959) found the ratio of the change in cell volume:change in chlorophyll *a* to be 1:1.68, whereas Wright and Soltero (1973) observed the ratio to be 1:3.47.

Wright (1959) noted that as the cell volume increased, the chlorophyll *a*:cell volume ratio decreased. The inference is that as the population increased, chlorophyll synthesis perhaps became limited. The lower ratio found in Canyon Ferry by Wright (1959) as compared to the ratio observed in this study might have been associated with this phenomenon. The cell volumes found by Wright were substantially higher

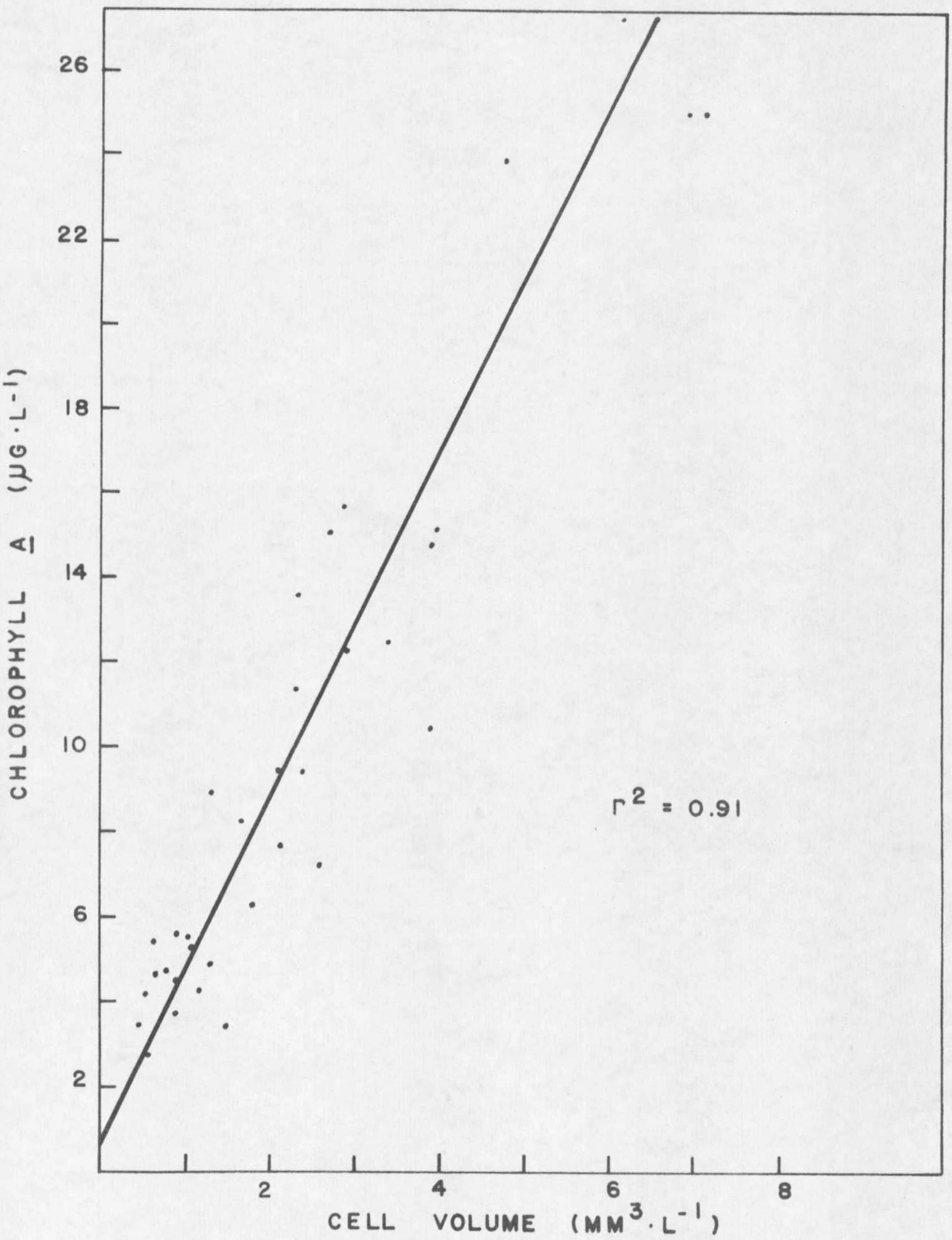

Figure 25. Correlation between average chlorophyll *a* concentration and average euphotic zone phytoplankton cell volume. The data are based on weekly samples taken from the entire reservoir during 1971 and 1972.

than what occurred in this study; e.g., the average cell volumes at Station 1 during 1957 and 1958 in Canyon Ferry were 5.90 $mm^3 \cdot L^{-1}$ and 3.04 $mm^3 \cdot L^{-1}$, respectively, compared with 1.41 $mm^3 \cdot L^{-1}$ and 1.37 $mm^3 \cdot L^{-1}$ during 1971 and 1972, respectively. Wright's (1959) average chlorophyll *a*:cell volume ratio for cell volumes ranging from 0-2.5 $mm^3 \cdot L^{-1}$ was 3.53 which was relatively close to the ratio determined in this study. When large cell volumes were prevalent, incomplete chlorophyll extraction also could have contributed to the low chlorophyll *a*:cell volume ratio. This could have been particularly important during the blue-green algal blooms.

The regression between chlorophyll *a* and cell volume indicated that when cell volume equals zero there would still be 0.70 $\mu g \cdot L^{-1}$ chlorophyll *a*. Analytical error in the chlorophyll determination may have been the cause of this discrepancy since the sensitivity of spectrophotometers become limited as absorbance falls below 0.05 (APHA 1971), i.e. when chlorophyll concentrations are low. Additionally, some of the absorbance measured in the extracts might have been due to a trace of some substance other than chlorophyll. An error such as this would also become more important at low chlorophyll concentrations.

Primary production. Net primary production was low during the early part of 1971. It increased through July, reaching a seasonal maximum of 1.68 g $C \cdot m^{-2} \cdot day^{-1}$ on 27 July. A secondary peak was noted on 17 August. Subsequently, primary production decreased and remained relatively constant through 13 September. The trend was similar during 1972 with the exception that the seasonal maximum of 1.52 g $C \cdot m^{-2} \cdot day^{-1}$ was attained on 14 August. Figure 26 depicts the average seasonal primary production in Canyon Ferry Reservoir.

In 1971 yearly average primary production was highest at the upper end of the reservoir, while in 1972 Stations 2 and 3 appeared to be the most productive regions of Canyon Ferry (Figure 27).

Wright (unpublished data) determined net primary production at Station 1 during 1957-1958 by both the light bottle oxygen method and the empirical method using chlorophyll data. The yearly average primary production (both methods) calculated by Wright and the yearly averages for 1971 and 1972 calculated by the chlorophyll method were as follows:

STATION 1

Year	Light Bottle Method	Chlorophyll Method
1957	1.33	1.26
1958	0.93	0.97
1971	--	0.39
1972	--	0.49

*All values g $C \cdot m^{-2} \cdot day^{-1}$

The comparative data indicate that the empirical chlorophyll method gave a reasonable estimation of net primary production. Therefore, as with phytoplankton standing crop, primary production in Canyon Ferry declined from 1957-1958 to 1971-1972.

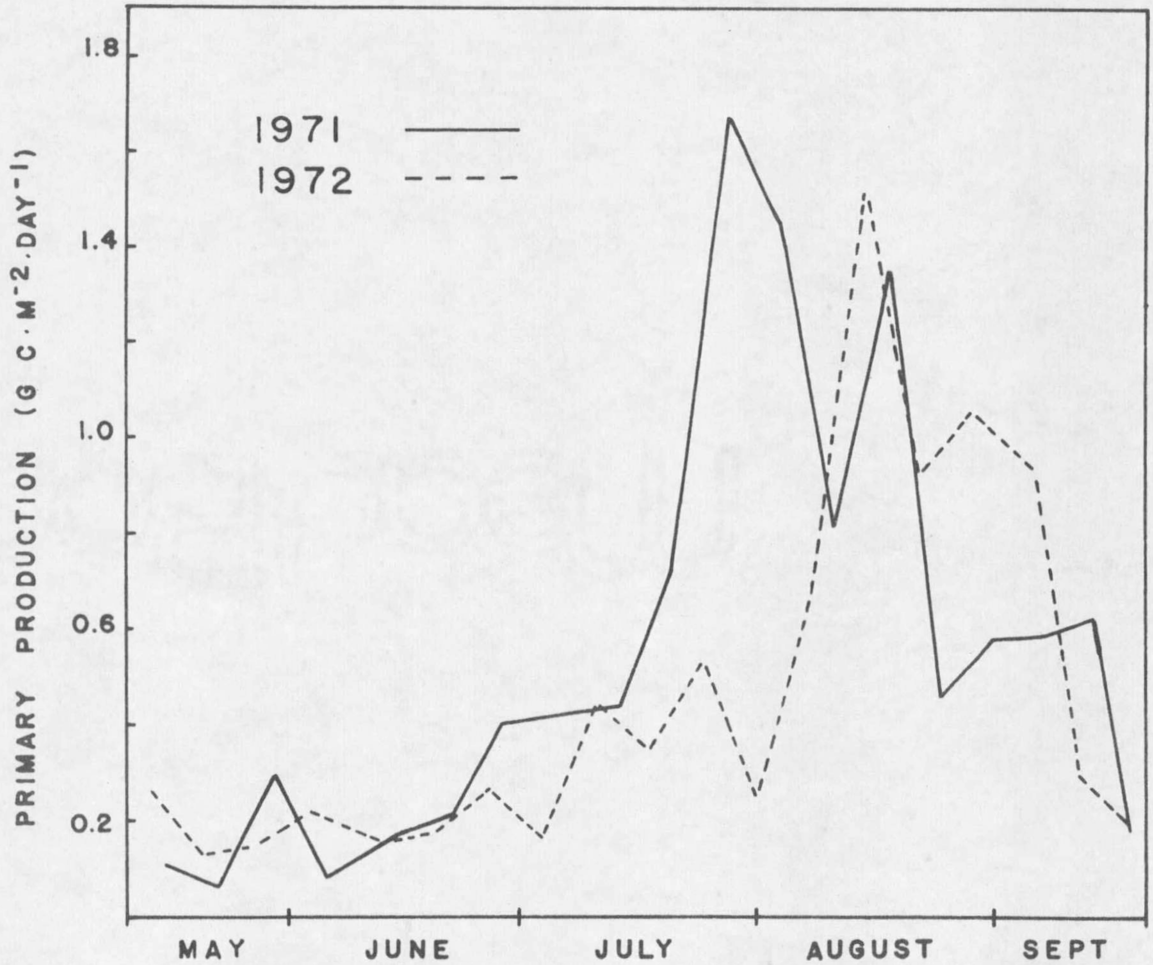

Figure 26. Average seasonal primary production observed in the euphotic zone of Canyon Ferry Reservoir during 1971 and 1972. The data are based on weekly averages during each sampling season.

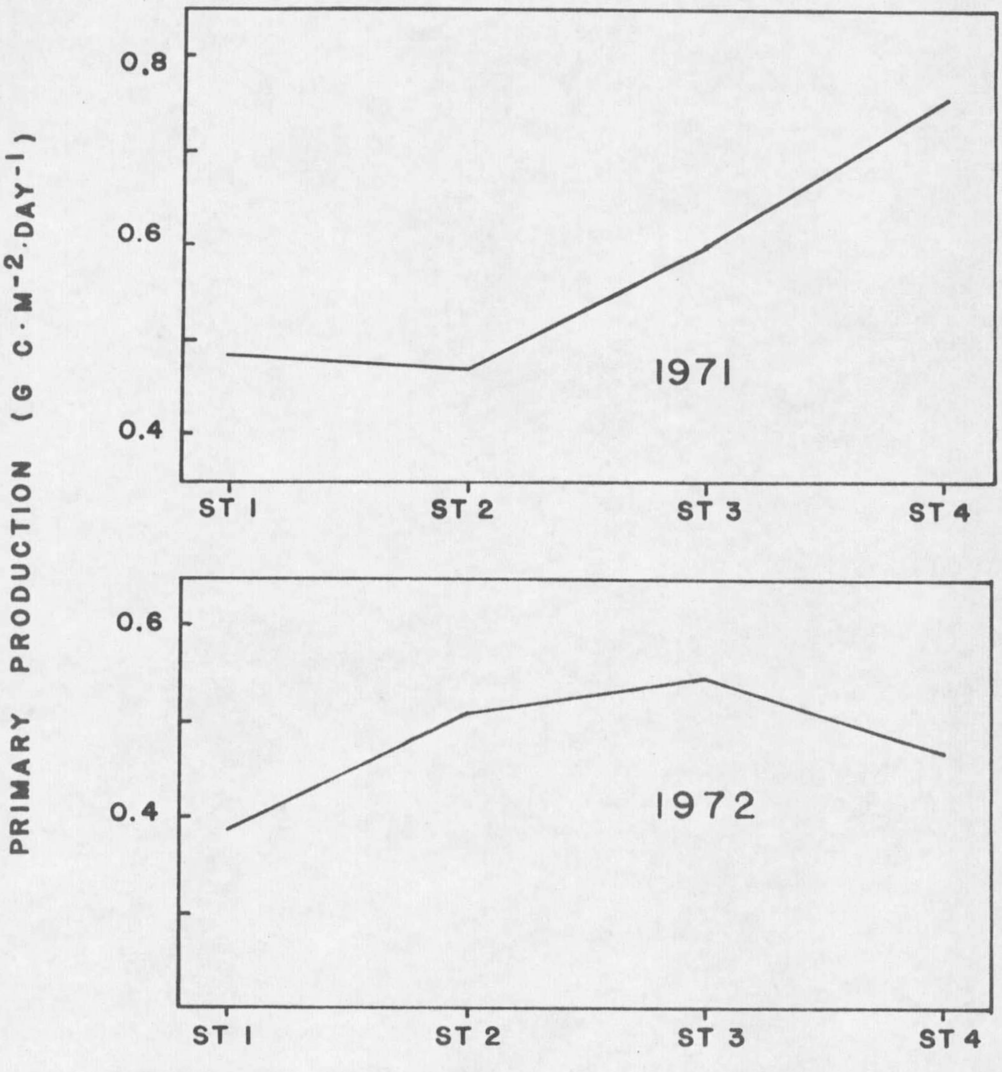

Figure 27. Horizontal distribution of euphotic zone primary production observed in Canyon Ferry Reservoir during 1971 and 1972.

Rodhe (1969) suggested that naturally eutrophic lakes tend to have average rates of net primary production during a growing season of 0.30-1.00 g $C \cdot m^{-2} \cdot day^{-1}$. Based on these arbitrary criteria, Canyon Ferry could be classified as a moderately productive lake since the average seasonal primary production for the entire reservoir was 0.52 g $C \cdot m^{-2} \cdot day^{-1}$ in 1971 and 0.48 g $C \cdot m^{-2} \cdot day^{-1}$ in 1972.

Assuming a photosynthetic quotient of 1.2, values of primary production in terms of g $O_2 \cdot m^{-2} \cdot day^{-1}$ can be obtained by multiplying g $C \cdot m^{-2} \cdot day^{-1}$ by a factor of 3.2.

SUMMARY

Canyon Ferry Reservoir is located approximately 24 km (15 mi) east of Helena, Montana. Its main uses are power production, flood control, irrigation, recreation, and supplemental water supply for the city of Helena. Canyon Ferry, a Missouri River mainstem reservoir, was impounded in 1953, and at maximum pool elevation its main morphometric dimensions are as follows: length, 40.2 km (25 mi); maximum breadth, 7.2 km (4.5 mi); and average depth, 17.8 m (58.4 ft). The reservoir was created by impounding the Missouri River which is formed by the confluence of the Gallatin, Madison, and Jefferson rivers at Three Forks, Montana.

Eight permanent stations were sampled: four in the reservoir, two in the Missouri River above Canyon Ferry at Toston and Townsend, one in the Missouri River below the dam, and one in the Helena Valley irrigation canal. The Gallatin, Madison, and Jefferson rivers were also sampled upstream from their confluence.

Inflows to the reservoir were low during the early part of each year, but began to increase in April and reached their peak during late June. After snow melt subsided, the inflows declined markedly. Large outflows were witnessed during May and were indicative of reservoir drawdown in preparation for spring runoff. During 1971 the reservoir was drawn down substantially more than during 1972; therefore, more reservoir bottom was exposed to the atmosphere in 1971 than in 1972 (Figure 3). Water retention times were shortest during May and were longest during summer when maximum surface elevations were attained.

Average water retention times were approximately 135 days.

Average turbidity was relatively high in the Missouri River at Toston, Townsend, and Station 4 within the reservoir. Canyon Ferry acted as a turbidity trap since most of the turbidity settled out in the upper 16 km (10 mi) of the reservoir (Figure 7). Highest turbidity was observed during spring runoff and was significantly correlated with relatively high phosphorus concentrations at Toston and Townsend. This could be partially associated with base exchange equilibria between the water and suspended sediments.

As a result of deep-water withdrawal, Canyon Ferry was an effective heat trap. This effectiveness was demonstrated by its relatively large summer heat income and the outflow temperature which was generally lower and increased at a slower rate than the inflow temperature.

Inflow conductance was lowest during spring runoff as a result of the dilution by snow melt. There was approximately a two-month lag from the time the relatively dilute inflow waters entered the reservoir until the outflow exhibited a substantial decrease in conductance (Figure 6); hence, a major reservoir effect was to increase the time for any chemically distinct seasonal inflow to be reflected in the outflow.

Isotherms and conductivity isoclines show that Canyon Ferry became stratified during June each year. Stratification was relatively intense in the lower reaches of the reservoir but became less pronounced progressing up-lake. This could be attributed to relatively strong winds which blew directly toward the upper end of the lake. Isotherms and conductivity isoclines also indicate that the winds could have caused some upwelling near the dam as well as initiating internal seiches within the reservoir.

Canyon Ferry Reservoir can be characterized as a bicarbonate water with calcium as its most abundant cation. Generally, the cations and anions behaved in a conservative manner. Any decreases in the concentrations of cations and anions within the reservoir during the regular sampling seasons (mid-May to mid-September) could be explained by dilution from runoff.

Oxygen concentrations were homogeneous during the early part of the season. After the reservoir became stratified, concentrations in the hypolimnion began to decrease because of decomposition of organic material. By mid-late August, the 2 $mg \cdot L^{-1}$ oxygen isocline was present along the entire bottom of the reservoir. The pH profile was similar to that of oxygen. Highest pH in the euphotic zone was observed during August. During that time pH was usually above 8.3; thus the concentration of free carbon dioxide was low while bicarbonate accounted for the majority of the total alkalinity.

Similar to the other chemical parameters, the nutrients were well mixed at the beginning of the season. However, with the onset of thermal stratification, concentrations in the epilimnion declined while the concentrations in the hypolimnion increased. The only exception was ammonia, the concentrations of which were quite variable throughout much of the sampling season.

Peak storage of ammonia occurred concurrently with the rise in surface elevation subsequent to spring drawdown. Exposure of organic material in the sediments to the atmosphere during drawdown probably resulted in more rapid rates of decomposition and ammonification. When water levels were again elevated, large quantities of ammonia could have been released to the water, therefore accounting for the high storage of ammonia. Ammonia soon declined and was accompanied by a sharp increase in nitrate, indicating that nitrification was occurring (Figure 15). Ortho-phosphorus storage was maximal during late June to early July and appeared to be related primarily to regeneration within the reservoir (Figure 16).

During the summer the Gallatin River was the only significant contributor of nitrate to the Missouri River headwaters. Most of that nitrate was utilized in the river upstream from Toston and never reached the reservoir.

Figure 28 summarizes total nutrient loads at the various Missouri River stations for an average mid-May to mid-September period, i.e. the regular sampling period. The average storage of ammonia, nitrate, and ortho-phosphorus in Canyon Ferry for the same period is also presented.

The average total loads of nitrate and ammonia were 57% and 18% larger, respectively, in the Missouri River at Townsend than at Toston.

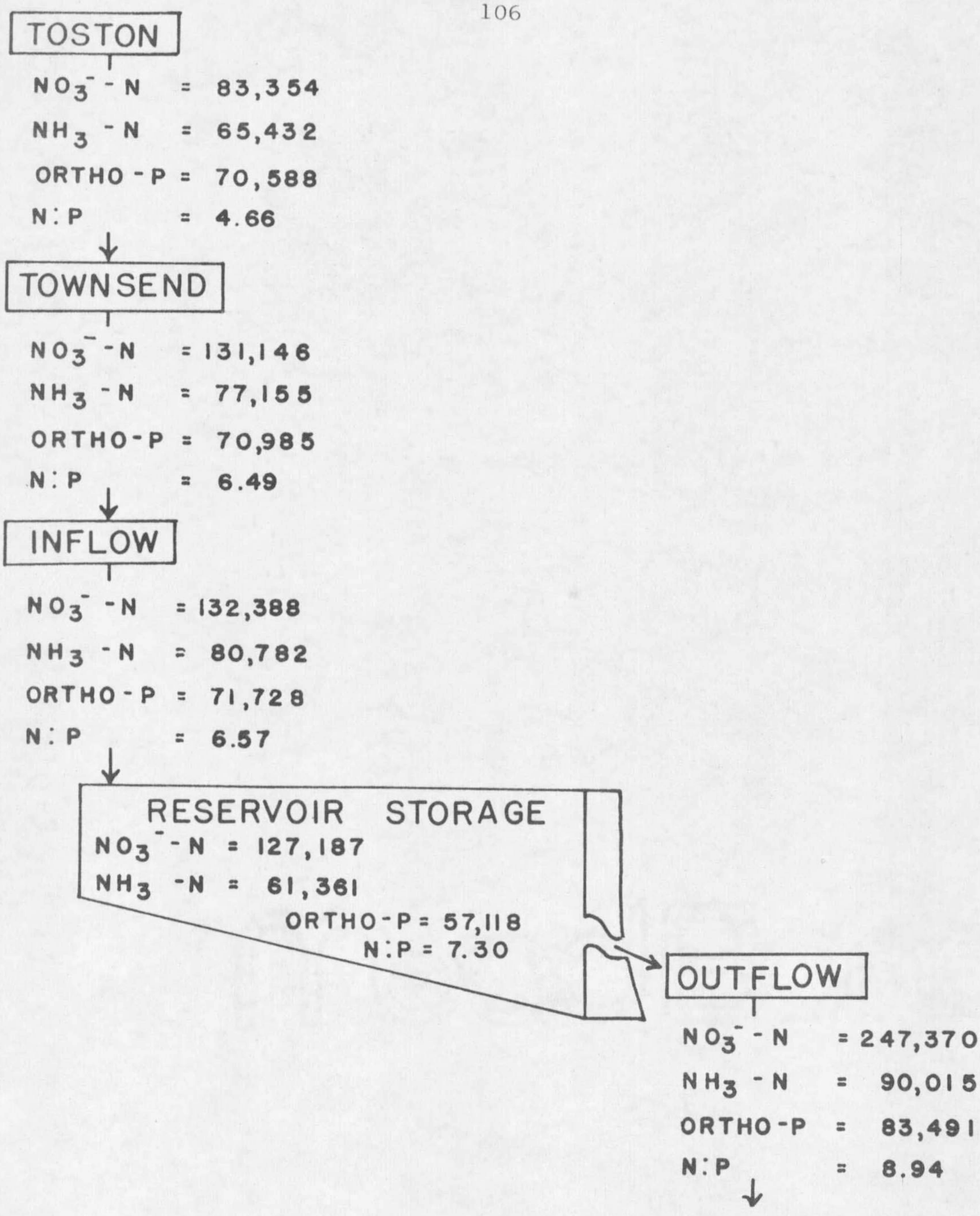

Figure 28. Total loads of nutrients (kg NH_3-N, NO_3^--N, and ortho-P) at the various Missouri River stations along with the average storage of nutrients in Canyon Ferry Reservoir observed during an average mid-May to mid-September sampling season. All values are averages from the 1971 and 1972 regular sampling seasons.

However, ortho-phosphorus loads were nearly equal at these two stations. Diversion of Missouri River water for irrigation of the Townsend Valley occurred above the Toston station; therefore, leaching of fertilized land by irrigation return flows was the most probable cause of the greater inorganic nitrogen loading at Townsend. The relatively high solubility of nitrate and ammonia and the low solubility of phosphorus in soil percolates could explain the relative differences between the inorganic nitrogen and phosphorus loads at Townsend.

Substantially larger amounts of inorganic nitrogen were observed in the outflow as compared to the inflow of Canyon Ferry (Figure 28). The most logical explanation of this is nitrogen fixation by blue-green algae during late summer. Release of fixed nitrogen would have been delayed until the algal cells decomposed and ammonification and nitrification had occurred. This process would have taken place largely in the sediments. Decomposition would have been more rapid when the sediments were exposed to the atmosphere than when submerged. Consequently, the extent of spring drawdown could have been an important factor in the relative amount of nitrogen recycled to the reservoir each year. In support of this hypothesis is the observation that during 1972 the area of reservoir sediment exposed to the atmosphere was only 70% of that exposed during 1971; correspondingly, the discharge of nitrate and average nitrate storage that occurred during 1972 were significantly less than those observed during 1971.

During the regular sampling season, mid-May to mid-September, an average of 31,053 kg NO_3^- + NH_3-N per month (124,215 kg N per 4 months) was released from the sediments and discharged (Figure 28). However, when data for an entire calendar year are considered, the average discharge of regenerated inorganic nitrogen was only 19,709 kg N per month (Table 13). This indicates that recycling of fixed nitrogen occurred to a greater extent during the regular sampling season than during the remainder of the year. Furthermore, it was during the beginning of the regular sampling season that the previously exposed sediments were being flooded. Also noteworthy is that Canyon Ferry maintained an average storage of 188,548 kg inorganic nitrogen during the regular sampling season in addition to the large loads of nitrogen being discharged.

More ortho-phosphorus was also observed in the outflow than in the inflow of Canyon Ferry. During the regular sampling season an average of 2,941 kg per month (11,763 kg P per 4 months) more ortho-phosphorus was found in the outflow as compared to the inflow (Figure 28). When considering the 10 1/2-month period of 12 June 1972 to 26 April 1973, an average of 8,434 kg per month (88,557 kg per 10 1/2 months) more ortho-phosphorus was present in the outflow than in the inflow (Figure 29). There was, however, no net change of total phosphorus within the reservoir when the phosphorus budget was determined for the 10 1/2-month period (Figure 29). This indicates that much of the

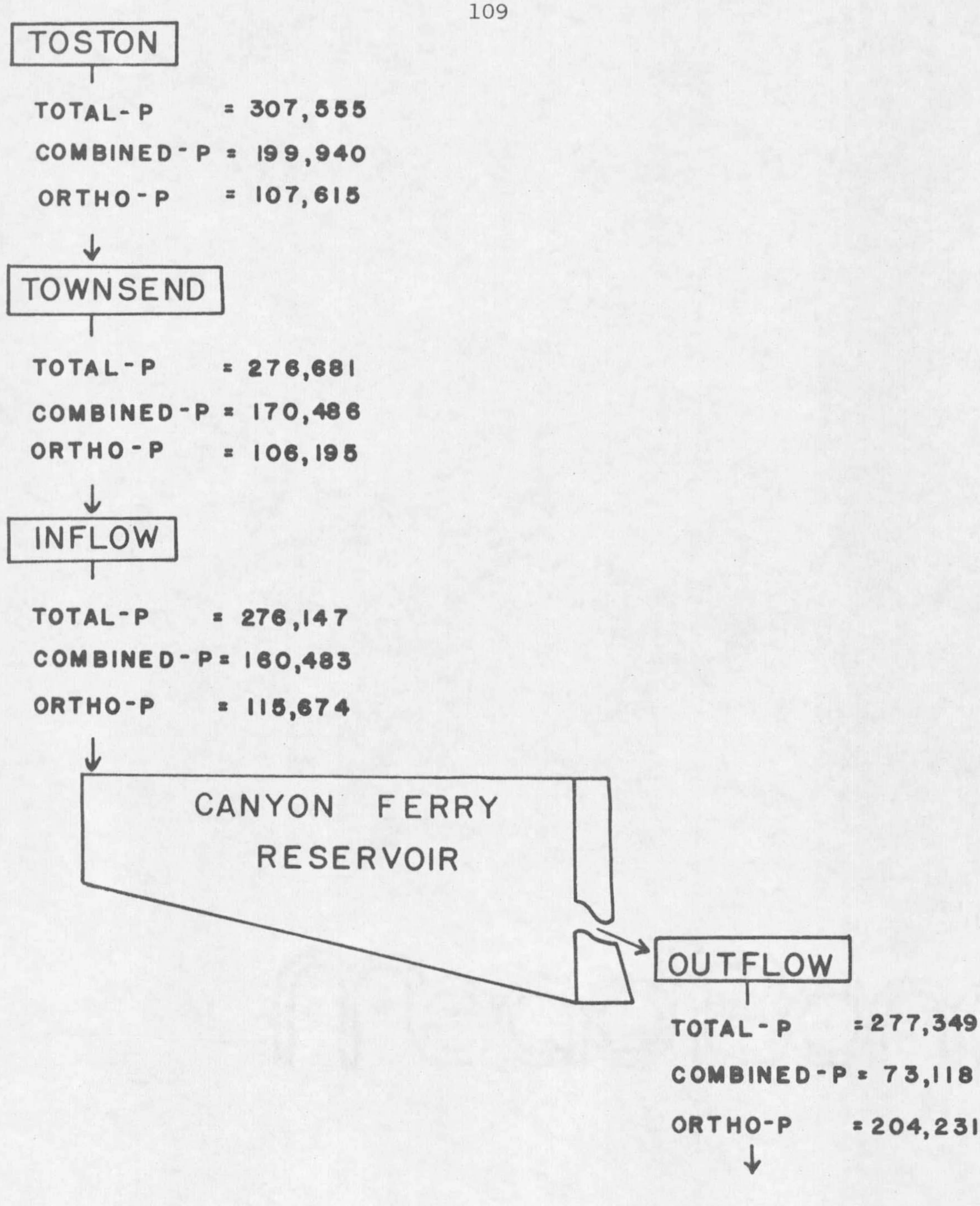

Figure 29. Total loads of phosphorus fractions (total-P, combined-P, and ortho-P) at the various Missouri River stations during the period 12 June 1972 to 26 April 1973. All values are kg P.

combined phosphorus which entered the reservoir was being mineralized to ortho-phosphorus and discharged.

The phytoplankton flora in Canyon Ferry was composed primarily of blue-green algae and diatoms. Cryptomonads, dinoflagellates, and green algae were also present. On a $mm^3 \cdot L^{-1}$ basis, *Aphanizomenon flos-aquae* was by far the most abundant phytoplankter in the reservoir, followed in decreasing order of abundance by *Fragilaria crotonensis, Stephanodiscus niagarae, Melosira granulata,* and *Diatoma elongatum* (Table 19).

Generally, standing crops were smallest near the dam and became progressively larger toward the upper end of the reservoir. Another notable feature of the phytoplanktonic horizontal distribution was that the diatoms had the largest average standing crop of any algae at Station 1. Progressing up-lake, the diatoms became relatively less abundant, whereas the blue-greens became relatively more abundant (Figure 18).

There was a spring diatom pulse each year, but the height of that peak probably was not observed since sampling did not begin until mid-May. Lowest absolute standing crops occurred during June when the cryptomonads and dinoflagellates reached their maximum relative densities. As the season continued, the blue-greens became more abundant while the diatoms declined in relative standing crop. The seasonal maximum standing crops were observed in July, 1971 and August, 1972. *Aphanizomenon flos-aquae* was the dominant phytoplankter during August each year.

Decline of the spring diatom peak was probably due to grazing by zooplankton (*Cyclops* and *Daphnia*) rather than nutrient limitation. After the zooplankton decreased in abundance, the phytoplankton, mainly diatoms and blue-greens, increased substantially. During 1971 the diatoms maintained relatively high standing crops through August, whereas in 1972 they declined after July.

Blue-green algae did not become prominent in Canyon Ferry until the surface waters reached 17°C. Bloom conditions did not occur until the temperature approached 20°C. Blue-greens are often thought of as thriving with warm temperature and high illumination. They have a competitive advantage over other algae because of efficient phosphorus uptake mechanisms and their ability to fix nitrogen. They also appear to have a more efficient mechanism than other algae for utilizing bicarbonate under low free carbon dioxide conditions. At the pH normally observed in Canyon Ferry during late summer, free carbon dioxide concentration was low and bicarbonate concentration was high.

Blue-green algae, because of their shape and gelatinous texture, are generally thought of as being relatively unaffected by grazing zooplankton. On the other hand, diatoms, cryptomonads, and other small flagellates are readily eaten and digested. In Canyon Ferry the zooplankton standing crops were larger during July and August of 1971 than in 1972. Similarly, during July and August of 1971, the diatoms sustained higher standing crops than during the same period in 1972. Thus it would appear that the diatoms supported zooplankton populations better than blue-greens.

The eutrophication problem has been discussed in several reviews (American Society of Limnology and Oceanography 1972, Beeton and Edmondson 1972, Hutchinson 1973, Lee 1970, National Academy of Sciences 1969, and Vollenweider 1970). Even with the voluminous literature on the subject, the exact definitions of oligotrophy, eutrophy, and eutrophication remain vague. When the terms oligotrophy and eutrophy were originally introduced into science, they meant poorly-nourished and well-nourished, respectively (Hutchinson 1969). Similarly, a eutrophic lake could potentially support a high level of production while an oligotrophic lake could not. Thus, lakes with low production are often referred to as oligotrophic while eutrophic lakes are considered highly productive.

Eutrophication should mean the process of becoming well fed (Hutchinson 1973). Natural eutrophication is an aging process which eventually terminates in the disappearance of the lake itself (Lee 1970 and Likens 1972). The process can be greatly accelerated by the activities of man and is then called cultural eutrophication (Hasler 1947).

Over the past several years, these terms have assumed different meanings in popular writings. Hutchinson (1973) states "Eutrophy in a New England lake before 1650 probably meant good fishing: now it is apt to mean a thick scum of blue-green algae."

In the interests of pure science, there is perhaps little value in constructing artificial schemes for classifying lakes. Trophic level classifications do, however, provide a way in which a large number of observations can be coordinated for comparisons. There are several indices including transparency, oxygen budgets, morphometry, nutrients, and primary production which can be used to assess the trophic level of lakes (Hooper 1969). The use of any one index is of extremely limited value, whereas the simultaneous use of several indices strengthens the classification of any particular lake. Care must be taken to determine whether any particular method of determining trophic level can be validly applied to the specific lake or reservoir in question. For example, based on specific surface loading of phosphorus, Canyon Ferry appeared to be as eutrophic as Lake Erie. However, since it is a reservoir with deep-water withdrawal, it has little, if any, net accumulation of total phosphorus. Therefore, Canyon Ferry does not fit this method of classification. Similarly, caution must be exercised when using total alkalinity decrease in the epilimnion during summer stratification as an index of trophic level. This index is based on alkalinity decreases as a result of photosynthetic calcium carbonate precipitation, whereas Canyon Ferry's alkalinity decline was due to dilution from spring runoff.

Based on areal hypolimnetic oxygen deficit, chlorophyll *a* concentrations, phytoplankton standing crops, and primary production, Canyon Ferry could be classified as a slightly eutrophic lake. This is not to suggest that it is a problem lake, rather that it is moderately productive. Since the boundary between the upper limits of oligotrophy and the lower limits of eutrophy are completely arbitrary, some authors (including Vollenweider 1970) suggest a third category, mesotrophic, which includes transitional lakes that lie somewhere between oligotrophy and eutrophy. Perhaps Canyon Ferry would best fit the transitional type of lake.

Table 22 demonstrates the extent of change in the trophic level of Canyon Ferry Reservoir from 1957-1958 to 1971-1972. This comparison pertains only to Station 1. However, the assumption could be made that similar changes were likely to have occurred in the upper reaches of the reservoir as well.

There is no evidence to suggest that Canyon Ferry's trophic level had become higher from 1957-1958 to 1971-1972; i.e., Canyon Ferry had not become more eutrophic during the above period. In fact, areal hypolimnetic oxygen deficit, average extinction coefficient, net primary production, chlorophyll *a*, and phytoplankton standing crops all indicate that Canyon Ferry's trophic and productivity levels have substantially declined since 1957-1958.

Impoundment of Canyon Ferry began in April, 1953, and maximum pool

Table 22. A summary of the change in trophic status of Canyon Ferry Reservoir from 1957-1958 to 1971-1972. Only data from Station 1 are used in the comparisons.

	1957		1958		1971		1972	
	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Areal Hypolimnetic Oxygen Deficit ($mg\ O_2 \cdot cm^{-2} \cdot day^{-1}$)	0.084	--	0.085	--	0.049	--	0.079	--
Average Extinction Coefficient per Meter of Euphotic Zone Depth	0.90	5.07	0.64	0.77	0.64	0.97	0.68	0.97
Ortho-phosphorus ($\mu g\ P \cdot L^{-1}$)	19	144	6	16	15	48	16	41
Net Primary Production ($g\ C \cdot m^{-2} \cdot day^{-1}$)	1.26	5.34	0.97	1.82	0.39	1.17	0.49	1.01
Chlorophyll *a* ($\mu g \cdot L^{-1}$)	11.72	70.56	8.19	15.82	5.95	13.53	6.12	17.17
Phytoplankton Standing Crops ($mm^3 \cdot L^{-1}$)								
TOTAL	5.90	29.75	3.04	8.02	1.41	4.99	1.37	5.53
Bacillariophyceae	1.85	6.19	1.98	7.50	1.03	4.81	0.75	2.62
Chlorophyceae	0.07	0.12	0.08	0.94	0.13	1.69	0.03	0.10
Cryptophyceae	0.76	2.63	0.44	1.52	0.05	0.15	0.07	0.40
Dinophyceae	0.06	0.22	0	0.02	0.01	0.07	0.02	0.12
Myxophyceae	3.13	29.21	0.54	4.61	0.19	1.02	0.50	5.23

elevation was not attained until summer, 1955. Therefore, the 1957-1958 study by Wright was performed on Canyon Ferry when it was a relatively new reservoir. On the other hand, the 1971-1972 study was performed on Canyon Ferry as an older reservoir. Inundation of bottom lands accompanying impoundment of new reservoirs normally releases inorganic minerals and organic materials to the water. Consequently, new reservoirs tend to have a high initial productivity potential, but later usually experience a decline in production and never seem to regain their initial levels. The evidence indicates that this also happened in Canyon Ferry.

CONCLUSIONS

(1) Canyon Ferry could be characterized as a bicarbonate water with calcium as the most abundant cation.

(2) During the summer the Gallatin River accounted for most of the nitrate observed in the initial reach of the Missouri River. However, much of the nitrate was utilized in the river between the headwaters and Toston and did not reach the reservoir.

(3) The increase in inorganic nitrogen loading at Townsend as compared to Toston was probably due to leaching of fertilized land by irrigation return flows in the Townsend Valley. There was no evidence of phosphorus enrichment between Toston and Townsend.

(4) The greater amount of inorganic nitrogen in the outflow as compared to the inflow of Canyon Ferry during the summer could best be explained by nitrogen fixation of the blue-green alga, *Aphanizomenon flos-aquae*.

(5) The extent of drawdown in preparation for spring runoff appears to have been a significant factor in the amount of nitrogen recycled to the reservoir each year.

(6) Loads of total phosphorus were nearly equal in the inflow and outflow. Much of the combined phosphorus that entered the reservoir was converted to ortho-phosphorus which left the reservoir.

(7) Deep-water withdrawal allows Canyon Ferry to discharge large loads of inorganic nitrogen and phosphorus which help alleviate many of the problems associated with high specific surface loading of nutrients.

(8) The phytoplankton in Canyon Ferry was primarily a blue-green algae/diatom flora. *A. flos-aquae* had the largest standing crops while *Fragilaria crotonensis*, *Stephanodiscus niagarae*, and *Melosira granulata* were also prominent.

(9) Canyon Ferry could be classified as a moderately productive or slightly eutrophic reservoir. However, there is no evidence to indicate that the reservoir has become more eutrophic since 1957-1958. On the contrary, Canyon Ferry appears to have become less eutrophic. Canyon Ferry lost its high initial level of productivity and appeared to be approaching a lower steady state level of productivity by 1971-1972. Consequently, the steady state level of biological production should continue throughout much of the life of the reservoir.

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