ROLE OF NITROGEN, PHOSPHORUS AND IRON IN OCCURRENCE OF ALGAL BLOOMS AT ABIQUIU AND COCHITI RESERVOIRS

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ABSTRACT

The alkaline reservoirs of Abiquiu and Cochiti in northern New Mexico were examined over the period of 1977-1979 to determine which nutrients influence the cyanobacterial blooms and to characterize phytoplanktonic activities. Nutrient bioassays were performed using Algal Assay Procedure (AAP) bottle test with Selenastrum capricornutum and Anabaena flos-aquae as indicator organisms. Additionally, an in situ method for evaluating nutrient and chemical additions was developed. Nutrients found to limit growth, singularly or when combined, included nitrogen, phosphorus and iron. Aquazine, copper sulfate and paraquat were evaluated as chemical control agents for phytoplankton. Decreases and changes in the population of phytoplankton were observed after copper sulfate and Aquazine additions; however, paraquat eliminated all phytoplankton.

Seasonal variations in phytoplankton populations, primary productivity, and nitrogen fixation were characterized. The diurnal changes in the depth distributions of cyanobacteria and nitrogen fixation were assessed during an Aphanizomenon bloom.

The dynamics of iron movement through the reservoir water were followed in laboratory experiments using radio-labeled iron. Iron associations are quite complex due to the appreciable salt level and alkaline ph of the water.

Nitrogen, phosphorus and iron concentrations were measured in reservoir water and at the inlets and outlets throughout this study. Nutrient balance analyses indicated that 46% of the nitrogen and 48% of the phosphorus entering Abiquiu Reservoir were retained. For Cochiti Reservoir

during a low runoff year nitrogen retention was 78% and phorphorus retention was 43%. In a high runoff year retention was 55% for nitrogen and 55% for phosphorus. Surface loading of nitrogen and phosphorus occurs at extremely high levels; however, the rapid movement of water through these reservoirs minimizes the impact of excessive nutrient loading. The abundance of phosphorus relative to nitrogen in influent waters strongly favors nitrogen-fixing cyanobacteria resulting in occasional Aphanizomenon blooms during the summer months.

Key words: Algal control, nitrogen, phosphorus, iron, Aphanizomenon, Selenastrum, Anabaena, nutrient budget, nitrogen fixation, primary productivity.

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RATIONALE FOR RESEARCH

Eutrophication of lakes and reservoirs with the occurrence of nuisance algal blooms is an increasing problem associated with the input of nutrients resulting from urban, agricultural, and recreational development. Algal blooms are an indication of deteriorating water quality. The blooms compound the problem by accumulating as floating algal or cyanobacterial masses and recreational users object to the unsightly foul smelling blooms. More significantly, public health problems are associated with cyanobacterial blooms, including possible release of toxins which may affect man and animals. As massive algal blooms sink to the bottom and decompose, the oxygen content of the water is depleted, and game fish may be killed.

Phytoplankton blooms of nuisance proportions have occurred frequently in both Abiquiu and Cochiti reservoirs in the past few years. The bloom producing organisms, Aphanizomenon flos-aquae and Anabaena sp., are both nitrogen fixing cyanobacteria (formerly termed blue-green algae). Based on primary productivity, chlorophyll concentration and total nutrient levels Cochiti Reservoir has been classed as a eutrophic reservoir and Abiquiu Reservoir has been classed as a mesotrophic reservoir (Barton and Johnson, 1978).

This research project stems from our interest in controlling phytoplankton blooms in these two southwestern reservoirs. Of course the most environmentally acceptable control measure for phytoplankton blooms is to reduce the quantity of nutrients in the body of water. Since Cochiti Reservoir is a new impondment, completed in 1975, and Abiquiu Reservoir has

only recently been used to establish a permanent pool of water, the sources of nutrients for the phytoplankton are primarily derived from the nutrient load flowing into the reservoirs and not from the nutrients already in the reservoirs. Point sources of nutrients entering the Rio Chama and Rio Grande above Abiquiu and Cochiti reservoirs may result from inadequate or malfunctioning waste treatment facilities. The absence of industrial and commercial operations in the watersheds of these reservoirs would suggest that the only type of point sources of nutrients would be domestic sewage. Non-point sources of nutrients would appear to be of major consequence for these reservoirs with nutrients derived from animal activity and erosion of natural and cultivated landscapes as well as other altered landscapes (e.g. forest fires, construction and developments). The non-point sources of nutrient additions are, in most instances, difficult or impossible to control.

In order to develop appropriate recommendations for the control of nuisance phytoplankton blooms it is necessary to characterize the nutrient-algal (or cyanobacterial) relationships in these reservoirs. To accomplish this, the following specific objectives were established:

(1) Determination of limiting nutrients for algal (or cyanobacterial) blooms in Abiquiu and Cochiti reservoirs,

(2) Evaluation of the contribution of cyanobacterial blooms to the nitrogen level and productivity of the reservoirs,

(3) Calculations of nutrient budgets for the reservoirs with emphasis on nitrogen and phosphorus, and

(4) Characterization of nutrient levels and physiological activities of the phytoplankton in the reservoirs.

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RESEARCH PROCEDURES

Sampling sites

These reservoirs were produced by earth-fill constructions in the mountainous regions of northern New Mexico. The location of these reservoirs and the sampling stations for each are indicated in figures 1 and 2. These sampling stations are the same as those that were employed in an earlier study of these reservoirs and carry the same designations (Barton and Johnson, 1978). Inflowing water samples were collected at the U.S. Geological Survey gauging stations above Abiquiu Reservoir and at the Otowi Bridge above Cochiti Reservoir.

In the reservoirs, all samples of water were collected with a plastic Kemmerer sampler. The depths sampled and replication of samples are specified for the various types of analyses conducted. Collections from the water column at a depth of 0.5 meter were referred to as surface samples. At the station near the dams (Station 1 at Cochiti Reservoir and Station 2 at Abiquiu Reservoir), a collection was made at 20 meters, which was near the bottom. Depths at other stations ranged from 8 to 15 meters and deep samples were not taken at these stations.

Phytoplankton examinations

Algal and cyanobacterial examinations were made on simple samples collected at the surface and at the 2 meter depth. The 750 ml samples were preserved with additions of Lugol's iodine, and phytoplankton were concentrated by the standard iodine settling method. The taxonomic key by Prescott (1970) was the reference for this identification. Enumeration was with a counting chamber fitted under the microscope (Jackson and

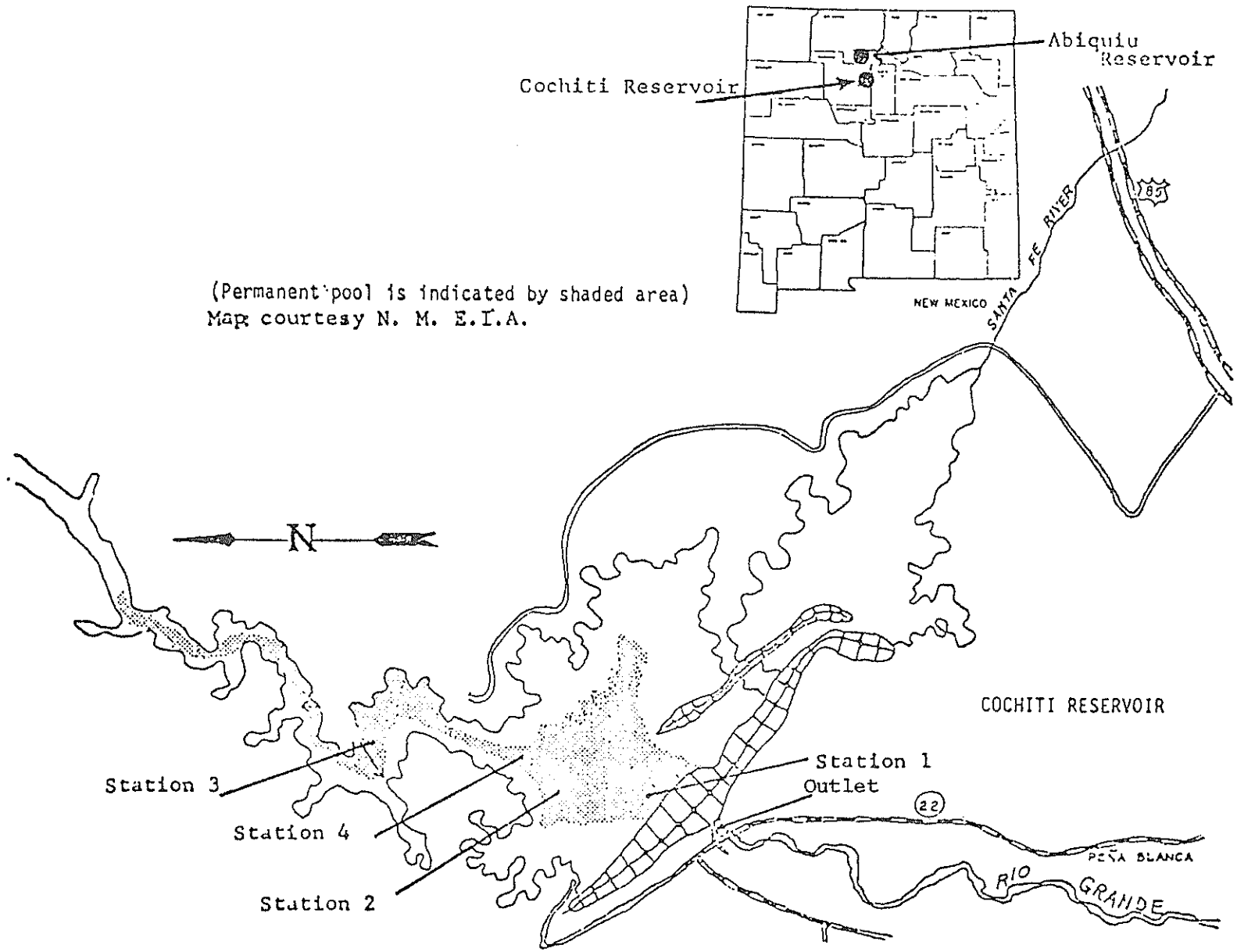

Figure 1. Cochiti Reservoir showing station location.

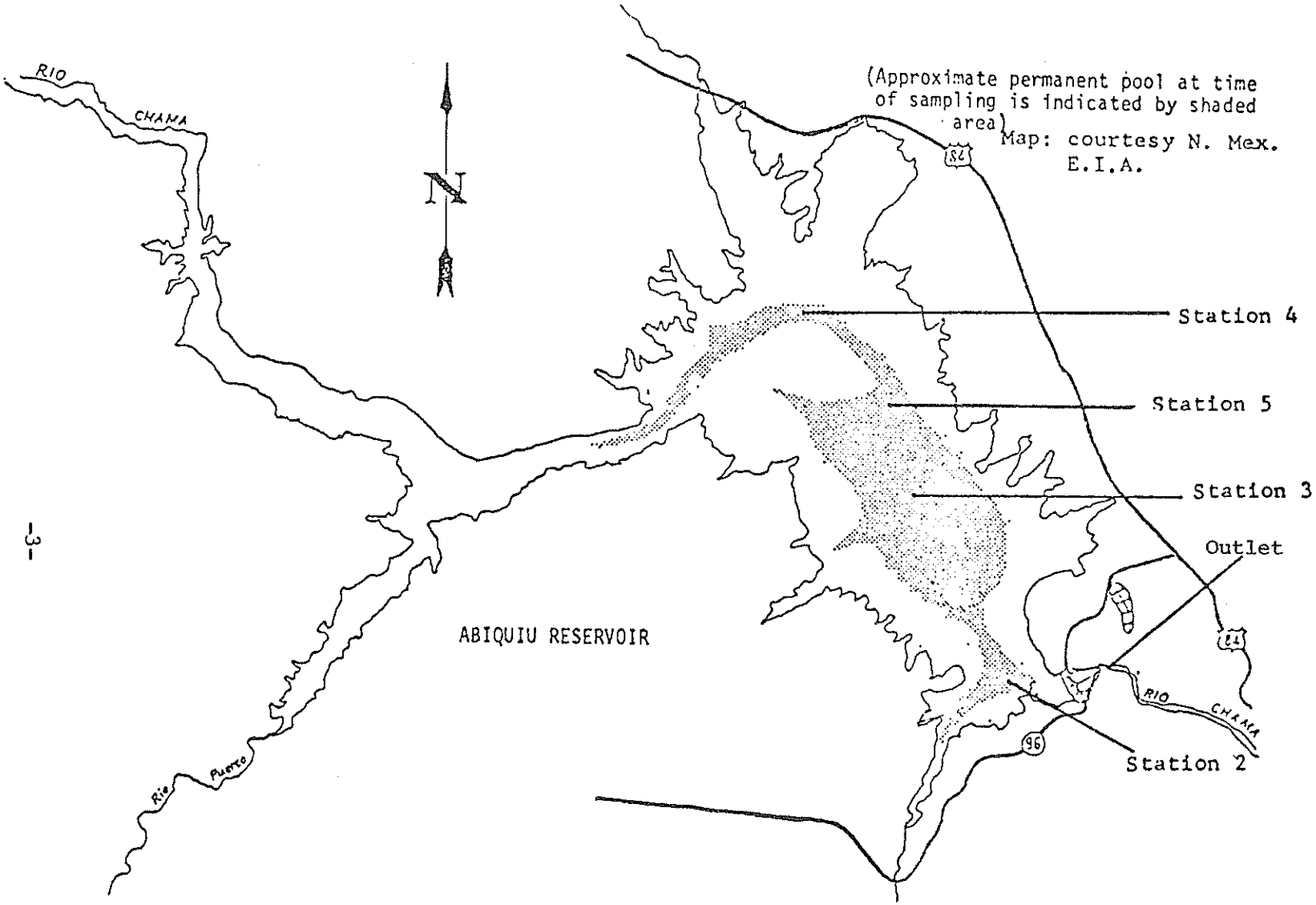

Figure 2. Abiquiu Reservoir showing station location.

Williams, 1962). The number of cells in a filament, the presence of heterocysts in filaments and the number of heterocysts were determined when cyanobacteria were present. Samples which were not preserved were routinely scanned to ensure that the dominant cyanobacteria were not being destroyed by preservation methods. The numbers of cyanobacteria were slightly lower in the preserved samples than in unfixed preparations; however, the floatation of the cyanobacteria made collection of representative samples extremely difficult and not highly reproducible. Values reported here are with I_2-fixed cells and are expressed as cells present in 1ml of reservoir water.

Primary productivity measurements

Primary productivity was determined using the C-14 method originally developed by Steemann Nielsen and modified by Kidd and Johnson (1971). Water samples were collected at 1 meter intervals and 125 ml was added to two transparent bottles (light bottles) and one opaque bottle (dark bottle) each containing 1.5 microcuries of radioactive carbon as $NaH^{14}CO_3$. The dark bottle provided a correction factor for non photosynthetic $^{14}CO_2$ fixation and exchange of C-14. These bottles were incubated in situ at the depth of collection; thus, primary productivity was measured under the conditions of temperature and light intensity prevailing in the environment.

After four to six hours of incubation, bottles were removed from the reservoir and placed in a dark chamber until the water could be filtered using a membrane filter with a 0.45 micron pore size. The membrane filter, containing both the phytoplankton and consumer organisms, was dried and the C-14 retained on the filter was measured using a Beckman LS-100 liquid scintillation counter.

Biological nitrogen fixation measurements

Nitrogen fixation was measured by the acetylene reduction method as described by Burris (1974). Phytoplankton were concentrated by sieving through Miracloth (Chicopee Mills, NY). The filaments were then resuspended in Miracloth filtered reservoir water to obtain an 100-fold concentrated suspension of cyanobacterial filaments. Ten ml of the concentrated filaments were added to a 24 ml serum bottle, the bottle stoppered, and acetylene injected to obtain a 13% acetylene atmosphere. The bottles were then incubated in the reservoir at the depths of collection for one hour. Activity was terminated by the injection of 2 ml of 5N H_2SO_4. Control bottles were prepared by addition of H_2SO_4 prior to injection of acetylene. Ethylene formation was measured using a Dohrmann 2460 gas chromatograph with a flame ionization detector fitted with a 9 ft x 1/8 in diameter column containing Porapak R. Column temperature was maintained at 40°C and helium gas was used as the carrier. Nitrogen fixation rates are tabulated as nanomoles of acetylene reduced per liter of water per hour corrected for any ethylene detected in control bottles. The specific activity of acetylene reduction was computed by dividing the nanomoles of acetylene reduced by the mg of filament nitrogen in the test bottle.

Limnological values

The pH measurements were made using a glass electrode pH meter and alkalinity was determined by the H_2SO_4 titration method (Golterman, 1969). Dissolved oxygen and water temperatures were determined in the reservoirs using a dissolved oxygen meter-thermometer (Yellow Springs Instruments). Transparency was determined using a Secchi disk. Using data provided

by the Water Quality Section of the New Mexico Environmental Improvement Division, regression equations were obtained relating Secchi disk readings to the depth of 1% light penetration for both Cochiti and Abiquiu reservoirs.

Chemical analysis

Nitrate (as nitrate plus nitrite), ammonium and orthophosphate were determined on 0.45 micron membrane-filtered water using a Technicon Autoanalyzer. Unfiltered water samples for total nitrogen and total phosphorus analyses were preserved in the field by H_2SO_4 additions as recommended by the Environmental Protection Agency (EPA, 1974). Total nitrogen (including nitrate and nitrite) was determined by employing standard Kjeldahl digestion procedures followed by determination of ammonium by the Technicon Autoanalyzer. Total phosphorus was determined spectrophotometrically by the molybdenum blue procedure after persulfate digestion (American Public Health Association, Inc., 1971). Samples for chlorophyll analysis (0.5 or 1 liter) were filtered through a glass fiber filter and the collected phytoplankton were extracted with 90% acetone using an Omnimixer. Chlorophyll and phaeophytin were measured spectrophotometrically with a correction for turbidity (Golterman, 1969). Sodium, potassium, calcium, magnesium, iron, manganese, copper and zinc concentrations in membrane-filtered water were measured by a Perkin-Elmer 306 atomic absorption spectrophotometer. Chloride and sulfate concentration in membrane-filtered water were measured using a Technicon Autoanalyzer. Conductivity of membrane-filtered water was determined at room temperature (25°C) using a Sybron-Barnstead conductivity bridge (Model

PM-70CB) with a YSI conductivity cell (Model 3403, Yellow Springs Instrument Company).

The organic carbon content of sediments obtained with a bottom sampling dredge was determined by the chromic acid oxidation method (Jackson, 1958; Allison, 1965). Nitrogen content of sediments was determined by distillation and titration of ammonium following Kjeldahl digestion (Bremmer, 1965). The total nitrogen content of collected algal filaments used in nitrogen fixation assays was measured following Kjeldahl digestion using either the Technicon Autoanalyzer or distillation and titration to measure ammonium. Total iron and soluble iron (i.e., iron remaining in solution after centrifugation at 20,000 x g for 20 min.) were determined in 200 ml samples digested with concentrated HNO_3 (EPA, 1974). After digestion was complete, samples were redissolved with HC1, diluted to 50 ml, and the iron concentration was determined by atomic absorption spectrophotometry.

Animal toxicity tests

Following the procedure established by Sawyer, et al. (1968), the presence of a toxin produced by Aphanizomenon flos-aquae was assayed using white mice. Frozen algal cells concentrated from reservoir water were mascerated and mixed with distilled water for four hrs at 5°C. This cell-free extract was injected intraperitoneally into several mice at various dose levels. Extracts from axenically grown Chlorella were used as controls. Since the toxin is fatal to mice, 100% mortality was used rather than LD_{50} (Sawyer, et al, 1968).

Microbiological studies

Heterotrophic aerobic bacteria were enumerated by standard plate count procedures using plate count agar (Difco) with incubation for 7 days at 20°C.

Bacterial activity was examined using metabolic activities which relied on the assimilation of radio-labeled glucose.

Laboratory bioassay for limiting nutrients

The EPA algal assay (bottle test) was used to identify limiting nutrients for phytoplankton growth (Environmental Protection Agency, 1971). After water samples were autoclaved for 30 minutes at 121°C and 20 psi, the water was filtered through a 0.45 micron membrane filter. Forty ml water samples were added aseptically to sterile 125 ml Erlenmeyer flasks and nutrients were added as specified in the report from the EPA Laboratory at Corvallis, Oregon (1971) (see Table 1). Cultures of the test organisms were obtained from the EPA Laboratory at Corvallis, Oregon. Three replicate flasks of each treatment were inoculated with 4×10^4 cells of Selenastrum capricornutum Printz or 4×10^5 cells of Anabaena flos-aquae (Lyngb.) DeBrebisson. Assays were conducted in the laboratory at 27°C with continuous cool-white fluorescent lighting at 400 ft-candles for S. capricornutum and 200 ft-candles for A. flos-aquae. After two weeks of growth, 10 or 20 ml samples of the culture medium were filtered through tared 0.80 micron filters and the filters were then dried (at 60°C) and weighed to measure the cell yield. Test organism growth in water samples without added nutrients and with addition of one or several components of the AAP medium was compared to growth in the complete AAP medium.

In situ bioassays of the effects of nutrient and chemical additions to reservoir water

The effects of nutrient additions, as well as the effects of several potentially inhibitory chemicals on the native phytoplankton, were

Table 1. Concentration of Algal Assay Procedure (AAP) medium nutrients in laboratory biosassys (EPA, 1971).

Macronutrients

Compound	Concentration (mg/l)	Element	Concentration (mg/l)
$NaNO_3$	25.500	N	4.200
$K2HPO_4$	1.044	P	0.186
$MgCl_2$	5.700	Mg	2.904
$MgSO_4$ $7H_2O$	14.700	S	1.911
$CaCl_2$ $7H_2O$	4.410	C	2.143
$NaHCO_3$	15.000	Ca	1.202
		Na	11.001
		K	0.469

Micronutrients

Compound	Concentration (g/l)	Element	Concentration (g/l)
H_3BO_3	185.520	B	32.460
$MnCl_2$	264.264	Mn	115.374
$ZnCl_2$	32.709	Zn	15.691
$CoCl_2$	0.780	Co	0.354
$CuCl_2$	0.009	Cu	0.004
Na_2MoO_4 $2H_2O$	7.260	Mo	2.878
$FeCl_3$	96.000	Fe	33.051
Na_2EDTA $2H_2O$	300.000		

studied under field conditions. A large sample of surface water was collected in a bucket. Translucent plastic containers with a cubic shape (Cubitainers, Hedwin, 609 5th Avenue, New York, NY) and a volume of 1 liter were then filled with surface water from the bucket. Nutrients and other chemicals were added to duplicate Cubitainers to obtain concentrations as indicated in the Results and Discussion section. The nutrient additions were made in the same chemical forms and concentrations used in laboratory bioassays. The Cubitainers were attached to a raft and suspended at the surface in the reservoir for 7 to 14 days. At the conclusion of an experiment, the Cubitainers were returned to the laboratory and one subsample removed for a chlorophyll determination and a second subsample preserved with Lugols solution and concentrated by settling for phytoplankton identification and enumeration as previously described.

Diurnal variation in phytoplankton distribution and activity

An experiment was conducted on September 7, 1979, to assess the diurnal variation in phytoplankton distribution and nitrogen fixation in Cochiti Reservoir during an Aphanizomenon bloom. Water samples were collected at Station 2, 1, 2 and 3 met or depths four times between dawn and sunset. Nitrogen fixation activity was determined using suspensions of cyanobacterial filaments concentrated 100-fold as previously described. The distribution of phytoplankton was determined by three types of measurements: (1) Total nitrogen content of concentrated filaments from the nitrogen fixation assays, (2) chlorophyll content of the suspension of concentrated filaments, and (3) identification and enumeration of phytoplankton by microscopic examination. In this experiment, 10-ml

samples of filaments, concentrated 100-fold, were frozen with solid carbon dioxide (dry ice) immediately after collection. The samples remained frozen until chlorophyll was extracted by homogenization in acetone using an Omnimixer. Chlorophyll and phaeophytin were measured in this extract as previously described. Two ml of the concentrated phytoplankton suspension were preserved by addition of 2 ml of FAA solution and subsequently examined for identification and enumeration of the phytoplankton. FAA was prepared by mixing 50 ml of 95% ethanol, 5 ml galacial acetic acid, 10 ml of 37% formaldehyde, 35 ml distilled water, and 5 ml glycerol (Peterson et al., 1977).

In order to compare this method with the iodine settling method, unconcentrated water samples were treated with Lugol's solution and phytoplankton concentrated by the settling procedure described earlier.

Diurnal variation in the distribution of heterotrophic microorganisms was investigated by a method based on respiration of ^{14}C-labeled glucose. One microcurie of ^{14}C labeled glucose was injected into a serum bottle containing 50 ml of unconcentrated reservoir water. These bottles were then incubated at the depth of collection. After an incubation period of one hour, activity was terminated by injection of 1 ml of 1M K_3PO_4. Upon return to the laboratory, the bottles were acidified and respired $^{14}CO_2$ was trapped in ethanolamine. The respired $^{14}CO_2$ was then determined by using a liquid scintillation counter.

Counts of viable bacteria in unconcentrated reservoir were made at surface and 5 m depths. Plating medium consisted of Plate Count Agar (Difco) with aerobic heterotrophic bacteria being enumerated.

Measurement of iron movements in reservoir water

To measure the dynamics of iron movement in reservoir water, several liters of water from Cochiti Reservoir were collected, placed in an ice chest and transported to the laboratory where radio-labeled iron experiments were conducted. The method employed was consistent with that reported by Murphy and Lean (1975). A liter of the reservoir water was filtered through Millipore membrane filters, with a 0.45 micron pore diameter. This filtered water was used to rinse the acid cleaned glassware and to wash the glass fiber filters or membrane filters which were used in the study. This washing procedure equilibrated the filters and glassware with the ions present in reservoir water and thereby provided the highest level of reproducibility.

Reservoir water, 10 ml, was placed in Pyrex test tubes and 10 l of $^{59}FeCl_3$ (3.4×10^{-4} M, 23,800 cpm; ICN Chemical and Radioisotope Division) was added with vigorous mixing. After incubating at 20°C for 15 min., the contents of the test tube were collected on a 25 mm diameter membrane filter, 0.45 micron pore diameter, previously washed twice with filtered reservoir water. The sample collected on the membrane filter was washed twice with 1 ml of filtered reservoir water. The amount of radio-labeled iron on the membrane filter was determined by using a Nuclear-Chicago gamma counter. Corrections were made for radio-labeled iron bound onto the membrane by using tubes of distilled water to substitute for the reservoir water as controls.

Variations in the above procedure were made to enable us to examine specific activities of iron. These variations are provided with the results and included such features as incubation at 4°C, addition of metabolic

inhibitors, addition of metal ions and the use of pretreated or selectively filtered reservoir water. In all cases, the volume of 10 ml in the reaction system was maintained. Activity in all experiments is expressed as cpm of Fe-59/10 ml of water tested with averages of triplicate tests being presented.

Analysis of reservoir water for humic acid

The presence of humic acid in Abiquiu and Cochiti reservoirs was determined using the procedure described by Martin and Pierce (1971). A 250 ml water sample was placed in a 500 ml separatory funnel and 10 ml of glacial acetic acid was added with vigorous shaking. Isoamyl alcohol, 30 ml, was added with additional shaking. The mixture was allowed to stand overnight until the two layers separated with humic acid being precipitated at the interface. The humic acid precipitate was collected on glass fiber filters and washed with distilled water and 95% ethanol. The precipitate was dissolved in 10.0 ml of 0.5 N NaOH and the absorption of the solution was determined at 540 nm using a Beckman 25 spectrophotometer. The standard for the humic acid absorption was obtained from the Menefee Formation in north-central New Mexico with extraction according to the procedure of Stevenson (1965). A 1% solution of humic acid had an absorbance at 540 nm of 2.4.

Nutrient budgets

Gloss (1977) considered possible nutrient sources for arid region reservoirs and concluded that for Lake Powell, only inflowing rivers and streams were significant. Important nutrient sources for Abiquiu and Cochiti reservoirs are probably limited to the inflowing rivers with the possible exception of significant nitrogen fixation by cyanobacteria. Based

on measurements of total nitrogen and total phosphorus in the inflowing and outflowing waters and daily flow rates obtained from the U.S. Army Corps of Engineers, weighted mean inflow and outflow concentrations were calculated and used to estimate nutrient budgets (Gloss, 1977).

RESULTS AND DISCUSSION

Water temperature and transparency

The water temperatures in the reservoirs over the period of this study were markedly similar to those observed in the 1976-1977 study (Barton and Johnson, 1978). The water temperatures were averaged for Abiquiu and Cochiti reservoirs and are given in tables 2 and 3. In both reservoirs, the spring warming of the water was noticeable in May and by June the surface water was about 20°C. At Abiquiu Reservoir, the water temperature dropped below 20°C in September while at Cochiti Reservoir, this temperature shift did not occur until October and November. The water temperature of 20°C would appear to be appropriate for phytoplankton growth and, therefore, the potential growing season for phytoplankton at Cochiti Reservoir would be about two months longer than at Abiquiu Reservoir. Cyanobacteria do not grow well at higher temperatures; however, surface water temperatures of 24 to 26°C should not be a limiting factor for growth of phytoplankton since the temperature at 5 m rarely exceeded 21°C. Although data for temperatures are reported here only at 5 m increments, temperatures were determined at 1 m intervals and temperature stratification was not observed with either reservoir.

Turbidity of the water is attributed largely to the presence of suspended clay-like particles. The entrance of this suspended material into the reservoirs, as best shown in the data from Cochiti Reservoir (table 4),

Table 2. Temperature of water in Abiquiu Reservoir. Values are given in °C.

Date	Station 2				Station 3				Station 4			
	Surface	5M	10M	15M	Surface	5M	10M	15M	Surface	5M	10M	15M
05/30/78	17.5	14.5	11.5	11	-	-	-	-	16	13	11	10
07/19/78	25	20	-	-	23.2	20	18	-	25.5	19.5	16.1	-
07/26/78	22	19.5	17.5	16.5	20	19.5	17.5	-	21	19	16.5	-
08/04/78	21.5	19.0	18.5	18.0	-	-	-	-	-	-	-	-
09/14/78	18.2	17.0	16.6	16.6	17.9	16.9	16.4	-	17.2	16.1	15.1	-
11/21/78	4.5	7.0	7.0	-	7.0	7.0	-	-	7.2	7.2	-	-
04/18/79	10.5	8.0	7.0	6.0	-	-	-	-	-	-	-	-
05/24/79	13.0	10.0	9.0	8.5	13.5	10.0	9.0	8.5				
06/12/79	21.5	13.5	9.5	9.0	20	14	10	9	21	13.5	10.0	9.0
07/10/79	26	19.5	14.5	13.5	24	19.5	14.5	13.5	25	20	15.5	13.5
08/09/79	21	20	15	19	-	-	-	-	25	21	16	14.5

Table 3. Temperature of water in Cochiti Reservoir. Values are given in °C.

Date	Station 1				Station 2				Station 3			
	Surface	5M	10M	15M	Surface	5M	10M	15M	Surface	5M	10M	15M
03/09/78	7.5	5.5	5	4	7.5	6	4	4	10.5	6	4.5	
05/16/78	15.5	13	12	9	17	13.5	12.5	9.5	17	14	14	-
06/13/78	19	16.5	15.2	13.8	19.5	16.3	15.8	13.9	19	16.2	16	
07/06/78	23	21.5	20	18	22	20.5	19	18	22.5	20.5	19.0	18
08/03/78	23	21.2	20.2	19.8	22	21.2	20.8	-	23.2	21.0	20.5	20.1
08/10/78	-	-	-	-	24	20	20	-	-	-	-	-
08/17/78	21	21	20	19	21	21	-	-	21.5	21.0	20.5	19.5
08/29/78	20	19.5	19	19	21	20	19.5	19	-	-	-	-
09/07/78	21	20	19	18.5	21	19.5	19	18.5	23	20	20	18.5
10/28/78	20	17.2	17.0	16.2	18.2	16.9	16.8	-	15	17.2	16.8	16.0
11/07/78	18	16.5	16.5	16.5	-	-	-	-	18	17	17	15.5
04/05/79	11	6.0	6.0	6.0	10.5	6.5	6.5	6.5	11	7.0	6.0	5.0
05/31/79	15.5	14.0	13.5	13.0	15.2	14.0	13.8	12.8	15	13.2	13.2	13.2
06/19/79	17.0	16.0	15.5	15.0	17	16.5	15.5	15.0	17	16.5	16	15
07/17/79	23.5	22.5	20.3	19.6	24.2	22.4	20.1	19.5	24.1	22.2	20.1	19.5
08/21/79	20	19	18	17.5	21	19	18.5	-	21.5	19	16.5	-

Table 4. Transparency level at Cochiti Reservoir. Measurements were with a Secchi disk and values are in centimeters.

Date	Station 1	Station 2	Station 3
03/09/78	62	58	-
05/16/78	30	25	150
06/13/78	35	31	27
07/06/78	100	70	48
08/03/78	-	122	32
08/10/78	141	118	-
08/17/78	265	187	76
08/29/78	201	200	-
09/07/78	200	140	81
10/28/78	157	145	122
11/07/78	282	241	144
04/05/78	60	58	43
05/31/79	14	14	10
06/19/79	44	38	28
07/17/79	159	204	93
08/21/79	36	-	23

occurs at the time of spring runoff from April to June and during the summe at irregular intervals at the time of summer rains. Water turbidity in Abiquiu Reservoir also is attributed to high volume outflow from other reservoirs north of Abiquiu. Due to the large snow deposits of 1977-1978, the water flowed into Abiquiu Reservoir at a high rate throughout the summer of 1978 (see table 5). Because water turbidity prevents light penetration, an abundance of phytoplankton would not be expected with low Secchi disk values; however, a considerable bloom of Aphanizomenon was recorded on September 14, 1978, when the transparency was not greater than 45 cm. This would suggest that the suspended solids do not inhibit cyanobacterial growth. Due to the high intensity of sunlight in the southwestern United States, light dispersed by the suspended solids becomes very important in supporting phytoplankton growth. As presented in table 6, one can relate Secchi disk readings to the depth of 1% light penetration.

Figure 3, indicating temperature, turbidity and phytoplankton blooms summarizes these results over the last four years.

Alkalinity, dissolved oxygen and pH values

Total alkalinity values in Abiquiu and Cochiti reservoirs (tables 7 and 8) were of greater extremes than observed in the 1977-1978 study (Barton and Johnson, 1978). It is expected that with high levels of photosynthesis, the level of CO_2 dissolved in the water would be low and therefore the alkalinity level would be low. This correlation was not always seen in the reservoirs examined. Very few phytoplankton were observed in the first part of 1978 at Abiquiu Reservoir and low alkalinity levels were obtained. High levels of Aphanizomenon were observed in August 1978 also

Table 5. Transparency level at Abiquiu Reservoir. Measurements were with a Secchi disk and values are reported in centimeters.

Date	Station 2	Station 3	Station 4
05/30/78	28	28	22
07/26/78	48	44	-
08/04/78	47	48	30
09/14/78	45	36	26
11/21/78	48	62	63
05/24/79	36	39	39
06/12/79	106	76	56
07/10/79	109	130	144
08/09/79	145	200	130

Table 6. Correlation of Secchi disk reading and depth of 1% light penetration at Cochiti and Abiquiu Reservoirs*.

Location	Depth of 1% Penetration (cm)	Sample Size	r
Cochiti, near Dam	$\frac{Y + 64.33}{2.100}$**	28	0.859
Cochiti, near Bland Canyon	$\frac{Y + 50.04}{1.863}$	28	0.942
Abiquiu, near Dam	$\frac{Y + 23.80}{1.426}$	4	.975
Abiquiu, Canones Creek Inlet	$\frac{Y + 16.91}{1.473}$	3	.899
Abiquiu, Chama River Inlet	$\frac{Y + 32.78}{1.839}$	4	.961
Abiquiu, all sample sites	$\frac{Y + 23.03}{1.532}$	11	.938

*Data kindly provided by the Water Quality Section, New Mexico Environmental Improvement Division

**Y = Secchi disk value in cm

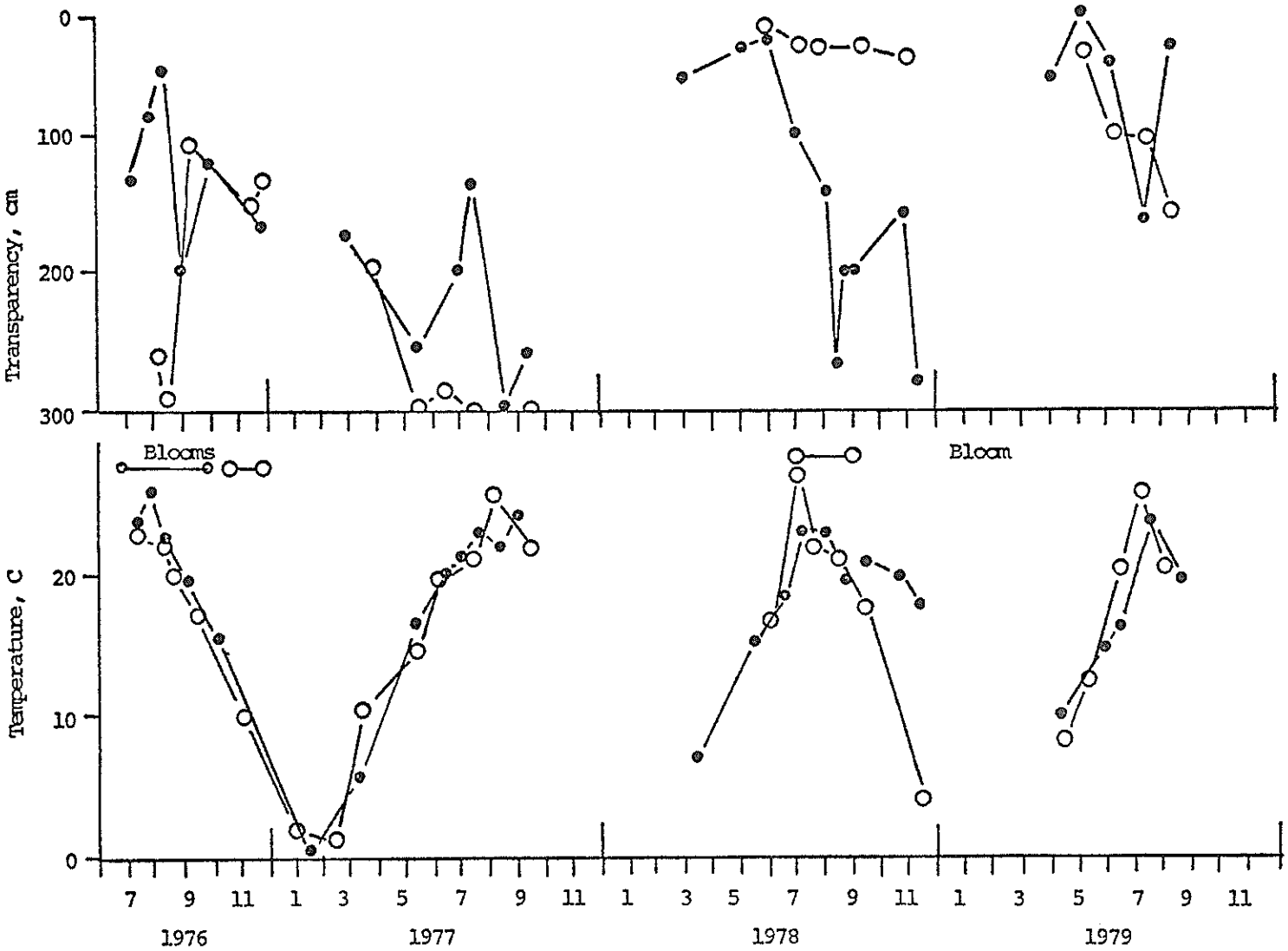

Figure 3. Water temperature and transparency of Abiquiu and Cochiti reservoirs. Cochiti Reservoir, closed circles, Station 1; Abiquiu Reservoir, open circles, Station 2. Phytoplankton blooms of over 80,000 cells/ ml are indicated.

Table 7. Total alkalinity of water at Abiquiu Reservoir expressed a mg/l of $CaCO_3$.

Date	Station 2			Station 3		Station 4	
	Surface	5m	20m	Surface	5m	Surface	5m
05/30/78	68.2*	65.1	56.9	67.2	66.2	62.6	56.9
07/19/78	67.5	67.5	-	64.6	64.2	-	66.9
07/26/78	68.8	66.5	60.8	64.6	-	61.8	65.6
08/04/78	65.6	67.4	69.4	67.8	66.9	66.1	73.0
09/14/78	70.3	72.2	76.0	71.2	73.2	72.2	76.0
11/21/78	89.3	95.0	87.4	93.1	98.8	-	-
04/18/79	172.9	179.4	135.3	177.5	174.8	-	-
05/24/79	131.1	137.2	133.8	125.4	129.4	125.0	129.2
06/12/79	113.6	112.6	112.4	132.6	124.1	131.8	119.2
07/10/79	128.4	147.8	120.5	125.4	147.8	132.2	134.1
08/09/79	87.4	86.3	-	90.8	72.6	80.6	72.6

*As $CaCO_3$, mg/liter

Table 8. Total alkalinity of water at Cochiti Reservoir expressed as mg/l of $CaCO_3$.

Date	Station 1			Station 2		Station 3	
	Surface	5m	20m	Surface	5m	Surface	5m
03/09/78	111.9*	111.7	-	107.3	110.1	126.9	106.1
05/16/78	90.3	82.9	-	84.0	83.4	80.8	79.8
06/13/78	68.2	68.2	76.6	65.1	67.2	69.3	71.4
07/06/78	63.6	60.8	66.5	66.5	60.8	68.4	69.4
08/03/78	62.7	79.8	78.8	79.0	75.1	77.3	101.3
08/10/78	79.8	83.2	82.1	81.7	81.7	-	-
08/17/78	79.4	76.9	81.7	82.5	81.3	85.5	86.6
08/29/78	40.3	43.7	41.8	41.8	-	-	-
09/07/78	86.4	86.4	93.1	89.3	90.2	85.5	91.2
10/28/78	-	95.0	104.5	95.2	96.7	99.2	93.1
04/05/9	181.1	178.1	177.5	175.2	174.0	176.3	180.1
05/31/79	125.4	144.5	149.7	146.3	135.3	120.1	135.7
06/19/79	129.9	131.5	-	130.7	129.9	133.4	135.3
07/19/79	131.7	139.5	-	133.8	121.6	122.4	134.5
08/21/79	186.9	180.2	-	175.2	175.2	140.6	180.2

*As $CaCO_3$, mg/liter

with low alkalinity levels. In 1979, moderate levels of phytoplankton were observed at Abiquiu Reservoir with high alkalinity values. Similarly, at Cochiti Reservoir the alkalinity values were high throughout 1979 even though the phytoplankton numbers went from low in the spring to high in the fall. Phenophthalein alkalinity was measurable only three times in this two-year study. Thus, it appears that the alkalinity measurements in these alkaline reservoirs are not reliable in indicating the level of phytoplankton activity. Perhaps these alkalinity measurements can be used to indicate that photosynthetic activity is not carbon dioxide limited.

Values for dissolved oxygen in Abiquiu and Cochiti reservoirs are presented in tables 9 and 10. These values are in general agreement with those obtained for the two previous years. When oxygen tension was examined at meter intervals, there was a difference in the oxygen content in the top 15 meters. Typical oxygen profiles are presented in Figure 4. In early spring, the oxygen content was uniform in the top 12 to 15 meters however, a marked decrease in oxygen level was seen in the summer when biological activity was greater and temperatures were higher. It should be recalled that no evidence of thermal stratification was observed.

The pH of the water in Abiquiu and Cochiti reservoirs were markedly alkaline with only one sample of water, from Abiquiu Reservoir on November 21, 1978 being acidic. The pH values at various stations and depths of the reservoirs are shown in tables 11 and 12. The most alkaline values obtained in the two-year study were in the last months of the study with a pH of 9.3 recorded for Abiquiu Reservoir and an 8.7 pH recorded for Cochiti Reservoir. The surface water is generally more alkaline than water at

Table 9. Dissolved oxygen at Abiquiu Reservoir in mg O_2/liter

Date	Station 2				Station 3				Station 4			
	Surface	5m	10m	15m	Surface	5m	10m	12m	Surface	5m	10m	12m
05/30/78	9.4	8.1	8.5	8.4	--	--	--	--	7.4	8.0	8.2	8.4
07/19/78	7.5	5.0	4.2	5.0	16.6	12.1	10.4	11.5	15.9	11.4	13.4	*
07/26/78	8.4	6.2	5.6	5.9	7.2	7.2	6.2	*	7.6	6.2	6.9	6.4
08/04/78	6.8	6.0	4.4	4.8	--	--	--		--	--	--	--
09/14/78	8.3	7.4	6.9	6.7	6.9	5.9	5.7	*	8.1	7.6	7.6	*
11/21/78	8.6	6.7	6.6	*	6.7	6.9	*	*	7.2	7.1	*	*
04/18/79	11.2	11.5	11.6	10.4	8.0	8.8	8.9	8.8	--	--	--	--
05/24/79	10.2	8.9	8.7	9.0	9.9	7.9	8.0	8.0	10.2	8.0	8.5	*
06/12/79	10.3	9.4	10.0	10.9	10.4	10.7	10.8	11.3	9.8	9.8	10.8	12.0
08/09/79	8.0	7.2	3.6	4.9	--	--	--	--	8.4	8.1	4.1	4.5

*Bottom

Table 10. Dissolved oxygen at Cochiti Reservoir in mg O_2/liter.

Date	Station 1				Station 2				Station 3			
	Surface	5m	10m	15m	Surface	5m	10m	12m	Surface	5m	10m	12m
03/09/78	10.4	13.2	12.4	11.4	10.4	12.3	11.7	11.7	10.4	7.3	8.4	2.3*
05/16/78	8.0	7.8	7.5	6.9	9.0	7.9	7.9	8.0	9.0	9.2	9.1	7.9
06/13/78	7.4	7.2	6.8	6.6	7.2	7.0	6.8	6.6	7.6	7.2	7.2	7.2
07/06/78	8.5	7.6	6.8	6.1	6.9	6.1	5.4	5.3	7.3	6.6	5.6	5.5
08/03/78	6.8	6.6	5.0	3.7	7.1	6.8	*	--	5.2	4.6	4.1	3.7
08/10/78	--	--	--	--	7.6	6.2	5.7	4.7	--	--	--	--
08/17/78	8.6	8.6	6.7	4.4	7.6	7.4	*	--	7.0	6.4	3.5	3.1
08/29/78	9.5	8.7	6.9	4.5	9.6	8.3	5.9	5.5	--	--	--	--
09/07/78	13.5	12.1	11.0	7.4	15.0	9.5	10.2	8.8	11.8	10.0	8.0	7.3
10/28/78	8.3	8.6	7.6	5.0	9.9	9.0	8.5	2.0*	11.2	10.4	7.4	7.5
11/07/78	8.2	8.0	7.6	7.4	--	--	--	--	7.8	7.0	6.8	6.3
04/05/79	11.2	11.2	11.2	10.8	9.8	9.7	9.8	9.7	9.0	9.6	9.6	9.4
05/31/79	7.8	7.9	8.2	8.2	8.0	7.9	7.9	7.9	8.3	8.5	8.5	8.5
06/19/79	8.2	8.6	8.2	7.8	12.9	13.0	12.7	12.4	9.8	9.7	9.7	10.0
08/21/79	8.8	7.8	6.1	2.4	11.9	10.1	7.1	6.7	15.2	11.8	10.8	11.1

*Bottom

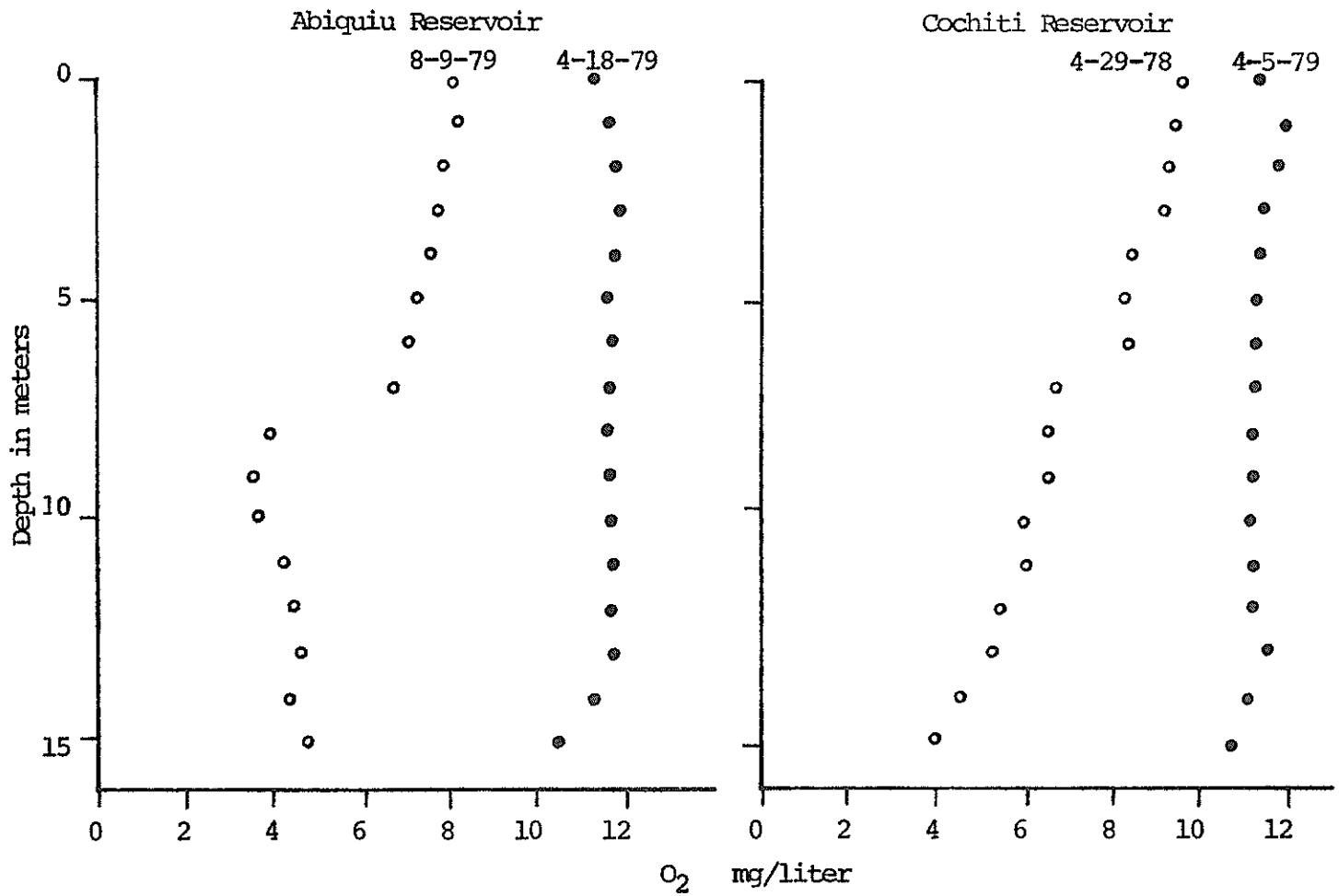

Figure 4. Typical oxygen profile in Abiquiu and Cochiti reservoirs.

Table 11. pH of water at Abiquiu Reservoir.

Date	Station 2			Station 3		Station 4	
	Surface	5m	20m	Surface	5m	Surface	5m
05/30/78	8.1	7.7	7.7	8.0	7.7	7.7	7.7
07/19/78	8.2	8.2	-	8.1	8.0	-	7.8
07/26/78	8.2	7.8	7.8	8.0	7.8	8.2	7.9
08/04/78	7.6	7.7	7.5	7.8	7.5	7.8	8.0
09/14/78	7.8	8.0	7.7	8.0	7.8	7.8	7.8
11/21/78	6.0	6.5	7.6	7.9	7.8	-	-
04/18/79	8.2	8.1	8.2	8.1	8.1	-	-
05/24/79	8.5	7.9	8.0	8.6	8.0	8.7	8.2
06/12/79	7.6	7.4	7.5	7.3	7.5	7.4	7.1
07/10/79	8.3	7.5	-	9.3	7.6	7.8	7.2

Table 12. pH of water at Cochiti Reservoir.

Date	Station 1			Station 2		Station 3	
	Surface	5m	20m	Surface	5m	Surface	5m
03/09/78	8.1	8.0	-	7.9	8.0	7.9	7.9
05/16/78	8.1	7.7	-	7.9	7.7	7.6	7.6
06/13/78	7.9	7.4	7.4	7.3	7.6	7.8	7.5
07/06/78	7.8	7.6	7.6	7.9	7.7	7.8	7.8
08/03/78	8.5	7.8	7.5	8.1	7.8	7.8	7.8
08/10/78	7.9	8.1	7.3	8.1	8.0	-	-
08/17/78	7.9	7.8	7.4	8.0	8.0	8.1	8.2
08/29/78	8.0	8.2	7.5	8.2	8.1	-	-
09/07/78	7.7	7.9	7.5	8.3	7.8	8.3	8.2
10/28/78	8.4	8.4	8.0	8.5	8.3	8.6	8.5
04/05/79	7.6	7.8	7.8	7.8	7.1	7.8	7.6
05/31/79	8.6	7.6	7.4	7.2	7.8	8.6	8.7
06/19/79	7.6	7.2	-	7.3	7.3	7.0	7.0
07/17/79	7.9	6.2	-	7.7	8.3	8.1	7.2
08/21/79	7.5	6.9	-	7.0	6.7	8.7	6.8

Table 13. Average pH values for Abiquiu and Cochiti reservoirs.

Abiquiu Reservoir

	Station 2			Station 3		Station 4	
Year	Surface	5m	20m	Surface	5m	Surface	5m
1976*	7.3	7.3	7.2	7.4	7.4	7.4	7.3
1977*	8.2	7.8	7.6	8.1	7.8	8.0	7.8
1978	7.7	7.6	7.6	8.0	7.8	7.9	7.8
1979	8.2	7.7	7.9	8.3	7.3	8.0	7.5

Cochiti Reservoir

	Station 1			Station 2		Station 3	
Year	Surface	5m	20m	Surface	5m	Surface	5m
1976*	8.0	8.1	7.6	8.2	8.0	8.3	8.1
1977*	8.0	7.9	7.7	8.1	7.9	8.0	7.9
1978	8.0	7.9	7.5	8.0	7.9	8.0	7.9
1979	7.8	7.2	7.6	7.4	7.4	8.0	7.5

*Values for 1976 and 1977 are from the report by Barton and Johnson, 1978.

lower depths due to photosynthetic use of bicarbonate, evaporation and high temperature effects. The alkaline character of the reservoirs is shown in table 13 where average pH values for the years of 1976 to 1979 are presented.

Nitrogen and phosphorus levels

In order to interpret chemical data from Abiquiu and Cochiti reservoirs, it is important to consider the differences in inflow and water storage volumes in the years of this study (data obtained from U.S. Army Corps of Engineers, unpublished). The snow pack in the mountains of northern New Mexico and southern Colorado produced below average runoff in the spring of 1978. Water storage in Abiquiu Reservoir increased from 19,000 to 57,000 acre-feet at the peak of the runoff in June; however, storage decreased to a typical volume of 17,600 acre-feet by August 15, 1978. Cochiti Reservoir was maintained with a storage volume of about 47,500 acre-feet during the 1978 spring runoff; however, storage in Cochiti was increased to 60,000 acre-feet in the summer and fall.

The snow pack in the winter of 1978-79 exceeded previous records, and resulted in unusually heavy runoff into the reservoirs in the spring of 1979. Storage in Abiquiu Reservoir increased to a maximum of 146,700 acre-feet in June and only gradually declined through the summer to 117,000 acre-feet by September 30, 1979 at the conclusion of this study. Cochiti Reservoir was managed quite differently. Storage in this reservoir increased rapidly from 47,300 acre-feet in May to a maximum of 184,400 acre-feet in June and then decreased to a volume of 46,500 acre-ft in July. While water storage was rapidly reduced to the permanent pool level, inflow and outflow rates remained unusually high until late August.

Table 14. Total nitrogen concentration in unfiltered Abiquiu Reservoir water as mg nitrogen/liter (N=2).

	Station 2			Station 3		Station 4		OUTLET
	Surface	5m	20m	Surface	5m	Surface	5m	
4/04/78	.255±.049†	.240±.084	.32	.317±.117	.360±.071	.435±.092	.295±.007	.395±.007
5/30/78	.695±.148	.430±.071	.470±.170	.770±.028	.545±.078	.435±.021	.625±.346	.570±.354
7/19/78*	.615±.092**	-	-	.760±.028**	--	.715±.049**	--	.510±.085**
7/26/78	.610±.014	.625±.233	.455±.035	1.200±.495	.570±.057	.725±.049**	.380±.071	--
8/04/78	.490±.057	.380±.042	.755±.262	.615±.148	.405±.064	.690±0	.415±.049	.505±.007
9/14/78	.625±.035	.495±.078	.460±.057	1.140±.014	.455±.021	.460±0	.395±.035	--
11/21/78	.27	.340±0	.475±.092	.385±.049	.375±.064	--	--	.380±.057
4/18/79	.45	.460±.014	.430±.028	.410±.057	.080±.057	--	--	.520±.028
5/24/79	.670±.028	.500±0	.635±.049	.580±.014	.570±.057	.635±.007	.495±.007	.525±.035
6/12/79	.110±.042	.120±.014	.130±0	.115±.007	.160±.042	.175±.021	.145±.007	--
7/10/79	.185±.106	.100±0	.245±.290	.300±.226	.260±.226	.39	.090±.042	.160±.085

†Standard deviation

*Station 1: Total nitrogen was 1.020±.283 mg/liter in unfiltered water and 0.54 mg/liter in membrane filtered water.

**Total nitrogen in membrane filtered water in surface samples for Station 2, 3, 4, and Outlet were: 0.49, 0.36, 0.42, and 0.59 mg/liter.

The highest total nitrogen concentrations in Abiquiu Reservoir were measured from late May through September of 1978 and in May of 1979 (table 14). During the summer of 1978 Aphanizomenon blooms occurred and the abundant filaments near the surface are the probable basis for the greater total nitrogen concentration in surface water than in water from the 5m depth at several stations. In the summer of 1979 total nitrogen concentrations were lower and blooms were not observed. The total nitrogen concentration in outlet samples was similar to that of the reservoir water samples.

Usually only a small percentage of the total nitrogen was in the inorganic form of ammonium (table 15) or nitrate (table 16) at the surface or 5m depth. Ammonium and nitrate were of greater significance in samples obtained at 20m and from the outlet. On May 30,1978, the outlet sample consisted of 42% ammonium nitrogen. Samples from 20m and the outlet obtained in the spring and summer of 1979 contained 30 to 75% or occassionally more of the nitrogen in the form of nitrate. The total nitrogen content of membrane filtered water was determined on samples collected on September 19, 1978, (table 14); 50-80% of the total nitrogen content of surface water samples was present in the filtered sample dissolved, although ammonium and nitrate were of minor importance at this sampling time. All of the nitrogen in the outlet sample on this date was found to be in the dissolved form. Because this separation was done only on one sampling date, it is uncertain whether dissolved forms of organic nitrogen are consistently a major portion of the total nitrogen.

The total nitrogen concentration in Abiquiu Reservoir averaged for stations 2-4 for the surface and 5m depths was 0.528 and 0.318 mg/liter for

Table 15. Ammonium nitrogen concentration in membrane-filtered Abiquiu Reservoir water as mg nitrogen/liter.

Date	Station 2			Station 3		Station 4		OUTLET
	Surface	5m	20m	Surface	5m	Surface	5m	
5/30/78	0.01	0.01	0.03	0.01	0.01	0.01	0.04	0.24
7/19/78	0.06	-	-	-	-	0.04	-	-
7/26/78	0.02	0.02	0	0.03	0.02	0.01	0.03	-
8/4/78	0	0.02	0.03	0	0.02	0.02	0	0
9/14/78	0.13	0.14	0.06	0.04	0.02	0.04	0.05	0.04
11/21/78	0.06	0	0.07	0.01	0.02	-	-	0.10
4/18/79	0.02	0.01	0.02	0.01	0.02	-	-	-
5/24/79	0.11	0.08	0.12	0.08	0.07	0.09	0.03	0.03
6/12/79	0.06	0.06	0.04	0.09	0.08	0.09	0.07	-
8/9/79	0	0	0.04	0	0	0.06	0.02	0.02

Table 16. Nitrate nitrogen concentration in membrane-filtered Abiquiu Reservoir water as mg nitrogen/liter.

	Station 2			Station 3		Station 4		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
4/04/78	0.012	0.016	0.057	0.024	0.025	0.059	0.065	0.076
5/30/78	0	0.020	0.033	0	0.016	0.008	0.013	0.050
7/19/78	0.005	-	-	0.004	-	0.005	-	0.066
8/04/78	0.007	0.003	0.004	0.002	0.002	0.003	0	0.039
9/14/78	0.012	0.028	0.021	0.010	0.015	0.027	0.028	0.028
11/21/78	0.031	0.029	0.024	0.028	0.029	-	-	0.010
4/18/78	0.157	0.121	0.131	0.131	0.114	-	-	-
5/24/79	0.025	0.164	0.211	0.010	0.146	0.004	0.146	0.302
6/12/79	0.027	0.036	0.109	0.033	0.036	0.027	0.036	-
7/10/79	0.003	0.037	0.185	0.003	0.029	0.007	0.026	0.200
8/9/79	0.003	0.010	0.132	0.003	0.005	0.018	0.013	0.164

1978 and 1979 samples respectively. These values are similar to averages for the summer of 1976 (0.434 mg/liter) and 1977 (0.355 mg/liter) reported by Barton and Johnson (1978) and suggest that the total nitrogen concentrations in this reservoir are rather stable. The higher average value in 1978 was associated with occurrence of nitrogen-fixing cyanobacterial blooms.

The total nitrogen concentrations in Cochiti Reservoir were lower in 1978 (table 17) than in Abiquiu Reservoir. While Abiquiu supported blooms of cyanobacteria during that summer, Cochiti had small populations of cyanobacteria which became quite numerous in late September and October. In 1979 samples, Cochiti Reservoir had even lower concentrations of total nitrogen from April through July, and the cyanobacteria population was low until August and September. Considering the capacity of the bloom producing cyanobacteria, Aphanizomenon, to fix nitrogen, it seems that high total nitrogen concentrations are more likely a result of cyanobacterial blooms than a cause.

While the ammonium concentration (table 18) and the nitrate (table 19) concentration are generally low compared to the total nitrogen concentration, there are occassional exceptions to this observation. Nitrate was a quantitatively important portion (30-40%) of the total nitrogen in all samples in June 1978 and in April and late May, 1979. Nitrate was usually a substantial (20-50%) fraction of the total nitrogen in samples from 20m at Station 1 and the outlet.

The total nitrogen concentration for all Cochiti Reservoir stations sampled at surface and 5m depths in 1978 was 0.378 mg/liter and in 1979 0.250 mg/liter compared to 0.974 in 1976 and 0.310 mg/liter in 1977

Table 17. Total nitrogen concentration in unfiltered Cochiti Reservoir water as mg nitrogen/liter (N=2).

	Station 1			Station 2		Station 3		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
3/09/78	.295±.007*	.370±.014	.270±0	.285±.049	.245±.007	.280±.113	.360±0	.225±.007
5/16/78	.540±.014	.685±.064	.690±.184	.395±.064	.435±.014	.365±.021	.355±.035	.327±.119
6/13/78	.415±.049	.290±.071	.380±.014	.350±.014	.330±.014	.365±.021	.355±.035	.327±.119
7/06/78	.345±.035	.305±.021	.255±.021	.395±.064	.450±.170	.58	.535±.120	.345±.021
8/03/78	.265±.007	.245±.007	.305±.106	.365±.035	.290±.014	.425±.064	.430±.014	.255±.007
8/10/78	.440±.099	.445±.035	.440±.014	.405±.049	.290±.014	-	-	.620±.028
8/17/78	.205±.035	.205±.049	.205±.049	.195±.035	.210±0	.350±.042	.373±.105	.280±.127
8/29/78	.270±.028	.250±.028	.200±.028	.290±.014	.230±.028	-	-	.405±.049
9/07/78	.465±.021	.415±.021	.310±.042	.540±.057	.395±.120	.970±0	.480±.028	-
9/28/78	.345±.021	.385±.007	.375±.021	.325±.021	.300±.014	.460±.085	.425±.021	.385±.021
10/07/78	.345±.021	.465±.078	.380±.113	-	-	.465±.120	.365±.092	.345±.035
4/05/79	.436±.008	.459±.024	.391±.024	.351±.016	.430±.097	.482±.008	.402±.008	-
5/31/79	.300±.014	.335±.007	.325±.007	.370±.042	.280±.028	.235±.007	.290±.042	.305±.035
6/19/79	.135±.064	.185±.007	0+0	.185±.007	.170±0	.205±.021	.235±.007	.235±.049
7/17/79	.075±.064	.095±.078	.015±.021	.120±.042	.040±.028	.025±.021	.150±.057	-

*Standard deviation

Table 18. Ammonium nitrogen concentration in membrane-filtered Cochiti Reservoir water as mg nitrogen/liter.

	Station 1			Station 2		Station 3		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
5/16/78	0.04	0.02	0.12	0.04	0.03	0.03	0.11	0.04
7/6/78	0.15	0.06	0.06	0.07	0.02	0.03	0.01	0.08
8/3/78	0	0	0.02	0	0.05	0.04	0.07	0
8/10/78	0.05	0.01	0.02	0	0.01	-	-	-
8/17/78	0	0	0.02	0	0.01	0	0.01	0.21
8/29/78	0	0	0	0	0	-	-	0
9/7/78	0.01	0.01	0.04	0.01	0	0.02	0.01	-
9/28/78	0	0	0.07	0	0.01	0.02	0	0.03
10/07/78	0.05	0.03	0.16	-	-	0.06	0.78	0.06
4/05/79	0.06	0.05	0.05	0.05	0.04	0.01	0.02	-
5/31/79	0.01	0	0.06	0	0	0	0	0.04
6/19/79	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.05
7/17/79	0.01	0.05	0.05	0.01	0	0	0	-
8/21/79	0	-	0.11	0	0	-	0.15	-

Table 19. Nitrate nitrogen concentration in membrane-filtered Cochiti Reservoir water as mg nitrogen/liter.

	Station 1			Station 2		Station 3		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
6/13/78	.051	.057	.132	.054	.063	.057	.059	.069
7/6/78	.004	.012	.128	.016	.008	.001	0	.050
8/3/78	.012	.012	.088	.009	.007	.036	.024	.035
8/10/78	0	0	.110	0	.006	-	-	-
8/17/78	0	.001	.110	0	.001	0	0	.118
8/29/78	0	0	.100	0	0	-	-	.112
9/7/78	.008	.005	.093	.007	.020	.004	.004	-
9/28/78	0	0	.019	0	.005	0	0	.017
10/07/78	0	0	.066	-	-	.011	.001	.054
4/05/79	.169	.171	.169	.167	.171	.159	.204	-
5/31/79	.141	.139	.156	.121	.121	.088	.093	.146
6/19/79	.005	.005	.136	.003	.002	.004	.059	-
8/21/79	.121	-	.148	.067	.091	.003	.024	-

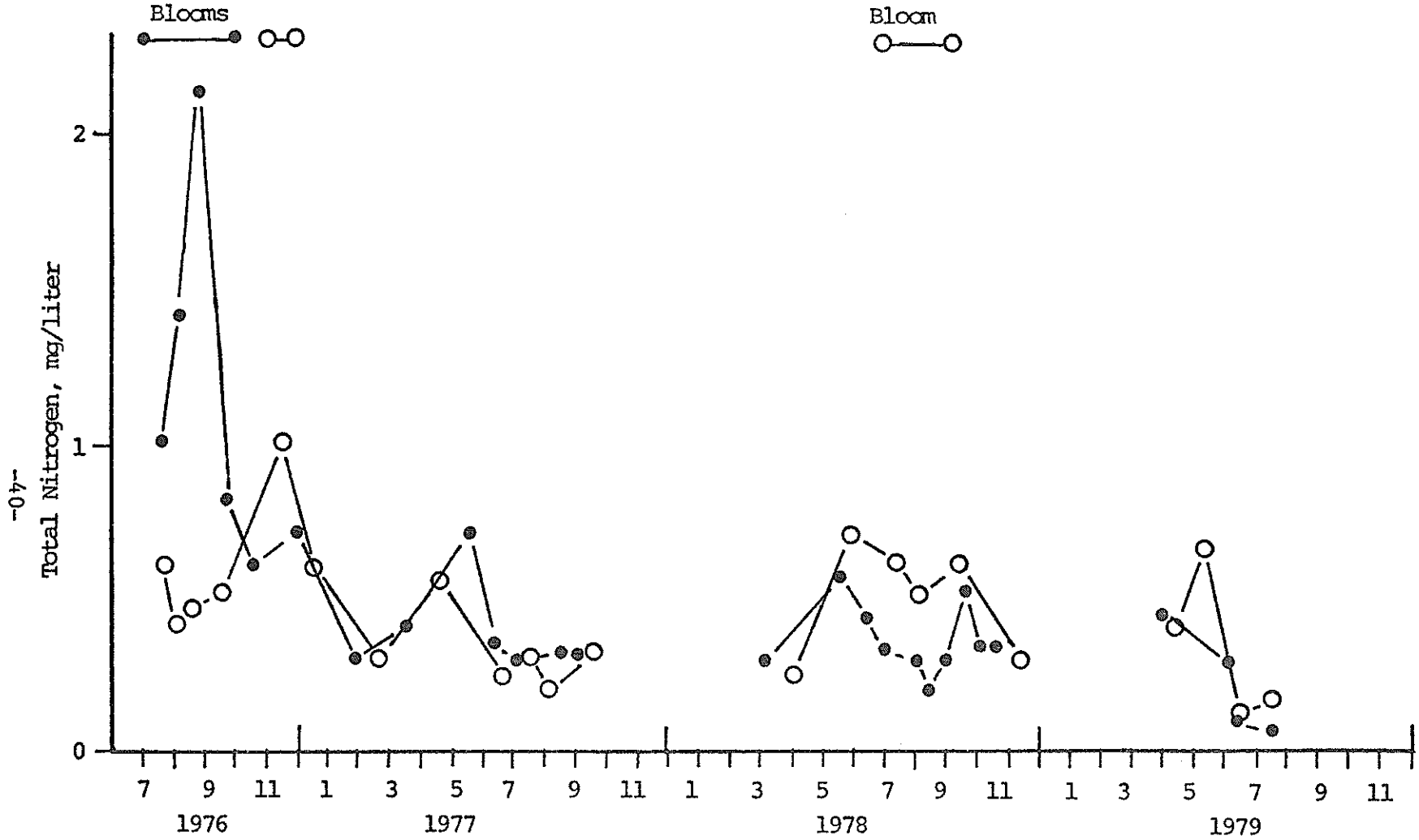

Figure 5. Total nitrogen values at surface level of Abiquiu and Cochiti reservoirs. Cochiti reservoir, closed circles, Station 1; Abiquiu Reservoir, open circles, Station 2. Phytoplankton blooms of over 80,000 cells/ml are indicated.

(averages for summer samples from Barton and Johnson, 1978). Thus the nitrogen content of Cochiti Reservoir water appears to be stabilizing at a much lower level than that found in 1976, the only year in which extensive Aphanizomenon blooms occurred throughout the entire summer and fall (Fig. 5).

The total phosphorus concentration in Abiquiu Reservoir (table 20 and Figure 6) tends to be slightly higher in the spring than in the summer, relecting the association of phosphorous with suspended sediments and the gradual settling of the sediments following spring runoff. As spring runoff occurs the concentration of phosphorus is higher nearer the inlet (Station 4) than in the main body of the reservoir. The association of phosphorus with suspended sedmients is also indicated by the higher total phosphorus concentration at the 20m depth and in the outlet than in surface or 5m samples at Station 2.

Only 5-10% of the total phosphorus was in the form of orthophosphate in surface and 5m samples (table 21). While the total phosphorus concentration overestimates biologically available phosphorus, the orthophosphate concentration probably more seriously underestimates biologically available phosphorus. In addition, because of the extremely dynamic nature of orthophosphate, reliable measurements are more difficult to obtain then for total phosphorus.

The average total phosphorus concentration in surface and 5m samples from Abiquiu Reservoir in 1978 and 1979 was 0.063 and 0.073 mg/liter respectively. These values are considerably above those measured at surface and 5m depths in the summers of 1976 and 1977, 0.032 and 0.013 mg/liter respectively (Barton and Johnson, 1978). Cyanobacterial numbers were sufficient to produce widespread surface blooms only in 1978. Similarly

Table 20. Total phosphorus concentration in unfiltered Abiquiu Reservoir water as mg phosphorus/liter (N=2).

	Station 2			Station 3		Station 4		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
5/30/78	.078±.003*	.076±.000	.144±.005	.076±.000	.072±.005	.090±.016	.122±.028	.154±.019
7/19/78	.056±.005	-	-	.080±.017	-	.072	-	.239±.014
7/26/78	.058±.008	.052	.131±.000	.108±.033	.048±.004	.046±.013	.044±.003	-
8/04/78	.040±.003	.040±.009	.098±.001	.028±.004	.032±.002	.078±.011	.068±.005	.090±.009
9/14/78	.048±.000	.050±.002	.141±.017	.086±.005	.058±.005	.098±.008	.074±.042	-
11/21/78	.046±.005	.0433±.000	.074±.002	.046±.005	.004±.008	-	-	.073±.000
4/18/79	.086±.002	.089±.003	.116±.005	.134±.001	.138±.001	-	-	.127±.001
5/24/79	.094±.006	.094±.006	.166±.008	.081±.004	.099±.007	.079±.001	.101±.004	.215±.020
6/12/79	.046±.047	.074±.001	.028±.004	.095±.003	.086±.004	.096±.002	.096±.005	-
7/10/79	.040±.002	.048±.011	.105±.011	.042±.000	.044±.002	.032±.004	.032±.004	.119±.010
8/08/79	.056±.005	.040±.009	.128±.006	.050±.005	.072±.004	.057±.011	.046±.005	.140±.030

*Standard deviation

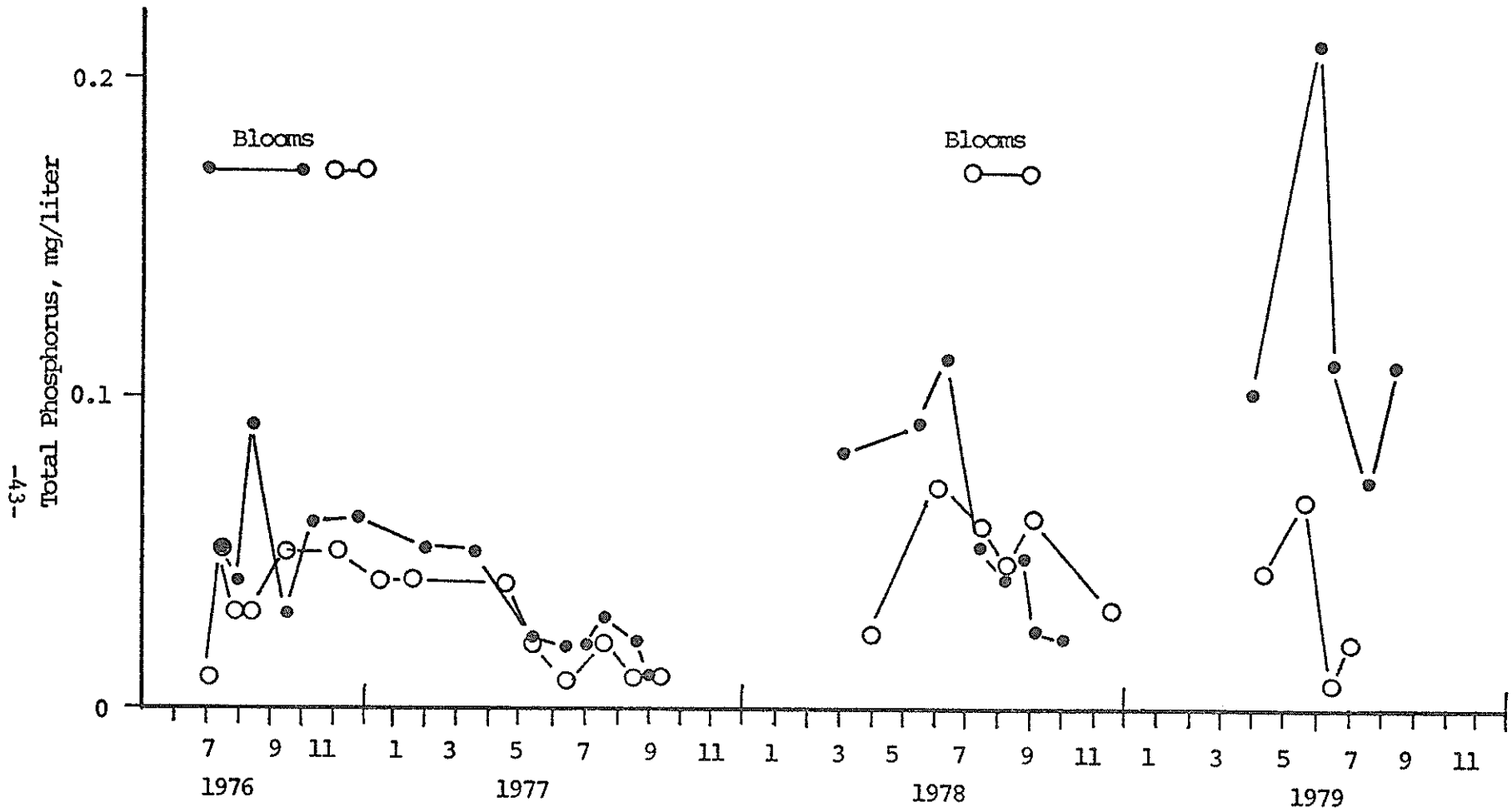

Figure 6. Total phosphorus at surface levels at Abiquiu and Cochiti reservoirs. Cochiti Reservoir, closed circles, Station 1; Abiquiu Reservoir, open circles, Station 2. Phytoplankton blooms of over 80,000 cells/ml are indicated.

Table 21. Orthophosphate concentration in membrane-filtered Abiquiu Reservoir water as mg phosphorus/liter.

	STATION 2			STATION 3		STATION 4		OUTLET
	Surface	5m	20m	Surface	5m	Surface	5m	
4/04/78	0	0	0	0	0	.001	0.002	0.002
5/30/78	0	0	0	0.010	0.020	0.009	0	0
7/19/78	0	-	-	0.001	-	0	-	0
8/04/78	0.007	0.009	0.011	0.003	0.001	0.003	0	0.001
9/14/78	0.001	0.001	0.001	0	0	0.001	0	0.003
11/21/78	0.012	0.012	0.001	0.009	0.008	-	-	0.009
4/18/79	0.004	0.008	0.008	0.008	0.008	-	-	-
5/24/79	0.007	0.007	0.016	0.007	0.005	0.005	0.005	0.007
6/12/79	.005	.009	.022	.003	.007	.013	.013	-
7/10/79	0.023	0.005	0.007	0.007	0.007	0.007	0.009	0.021
8/9/79	0.003	0.005	0.019	0.005	0.009	0.003	0.003	0.023

Gibson (1971) of the composition of various algal cells established that the N:P ratio of cells ranges from 10:1 to 15:1. Applying this criteria to Abiquiu Reservoir based on the N:P ratio, suggests that nitrogen was slightly limiting in 1978 and severely limiting in 1979.

The total phosphorus concentration in Cochiti Reservoir in 1978 (Table 22) exhibited a pattern similar to that observed in Abiquiu in the same year (Table 20). The total phosphorus concentration was highest in surface and 5m samples in the spring and began to decline after the June 13, 1978 sample collection as the sediment load from spring runoff began to settle to the bottom. The total phosphorus concentration in surface and 5m samples from Station 3, which is closer to the inlet, was almost always higher than the total phosphorus concentration on the main body of the reservoir (stations 1 and 2); indicative of the greater sediment load near the inlet. By late summer the total phosphorus concentration of the surface and 5m samples had decreased to low levels at all stations. A decrease in the total phosphorus concentration also occurred in the 20m sample from Station 1 and the outlet from spring to late summer; however, these samples usually contained more phosphorus than surface or 5m samples from Station 1, reflecting the settling of the sediments near the dam.

In 1979 the total phosphorus concentration of surface and 5m samples were highest on May 31, 1979 and, while declining through the summer, remained at considerably higher concentrations than during the summer of 1978. The much higher total phosphorus levels in Cochiti Reservoir than Abiquiu Reservoir in 1979 appears to be the result of management procedures allowing rapid flow rates both into and out of Cochiti Reservoir while water storage was lowered to typical pool size by mid-summer. Storage at Abiquiu,

on the other hand, was maintained much above the usual pool size and sediment settled in the larger storage volume without bringing about an appreciable increase in the total phosphorus concentration compared to the previous year. These differences in total phosphorus concentrations may have been responsible for the occurence of cyanobacterial blooms in Cochiti while not in Abiquiu in the late summer of 1979.

The mean total phosphorus concentration of surface and 5m samples from all Cochiti Reservoir stations was 0.070 and 0.128 mg/liter in 1978 and 1979 respectively. These concentrations may be compared to summer mean values in 1976 and 1977 of 0.052 and 0.033 mg phosphorus/liter respectively (Barton and Johnson, 1978). While summer values are lower in part because of exclusion of the high spring values, the effects of the rapid movement of water through Cochiti Reservoir on the mean total concentration in 1979 are quite evident.

Orthophosphate concentrations at surface and 5m depths for all stations averaged 0.011 and 0.030 mg phosphorus/liter in 1978 and 1979 respectively, corresponding to 16% and 23% of the total phosphorus during these two years (Table 22). Thus, not only was the total phosphorus higher in Cochiti Reservoir, but a greater proportion of the total phosphorus was in the immediately available orthophosphate form in Cochiti compared to Abiquiu Reservoir in both years of this study. The greater concentration of orthophosphate in Cochiti rather than Abiquiu Reservoir should favor larger populations of phytoplankton in the former reservoir.

The mean nitrogen: to phosphorus ratio, based on the total nitrogen and total phosphorus in surface and 5m depth samples, was 5.40 in 1978 and 1.95 in 1979. Thus the reservoir was limited by nitrogen in respect to

Table 22. Total phosphorus concentration in unfiltered Cochiti Reservoir water as mg phosphorus/liter (N = 2).

Date	STATION 1			STATION 2		STATION 3		OUTLET
	Surface	5m	20m	Surface	5m	Surface	5m	
3/09/78	.078±.002*	.088±.001	.072±.005	.086±.000	.084±.011	.116±.002	.102±.000	.086±.005
5/16/78	.090±.009	.122±.009	.077±.000	.110±.009	.122±.009	.155±.018	.214±.010	.106±.005
6/13/78	.110±.047	.104±.009	.108±.011	.087±.004	.096±.009	.102±.001	.113±.004	.091±.001
7/06/78	.052±.003	.063±.000	.086±.000	.074±.007	.055±.007	.077±.003	.099±.000	.063±.000
8/03/78	.042±.005	.047±.011	.090±.012	.052±.000	.046±.006	.097±.007	.092±.000	.072±.010
8/10/78	.044±.003	.056	.105±.010	.062±.008	.062±.008	-	-	.084
8/17/78	.052±.001	.067±.000	.111±.007	.067±.000	.070±.005	.084±.005	.081±.000	.109±.000
8/29/78	.029±.020	.046±.000	.058±.042	.057±.020	.062±.012	-	-	.092±.010
9/07/78	.020±.028	.042±.000	.074±.005	-	-	.052±.005	.050±.008	-
9/28/78	.020±.001	.024±.000	.052±.002	.029±.008	.034±.003	.032±.005	.030±.011	.048±.000
10/07/78	.014±.001	.023±.007	.044±.013	-	-	.040±.001	.041±.000	.028±.000
4/05/79	.098±.000	.098±.001	.106±.004	.100±.004	.102±.002	.097±.000	.096±.003	-
5/31/79	.213±.040	.199±.000	.172±.001	.171±.001	-	.204±.001	.188±.101	.249±.086
6/19/79	.112±.001	.124±.006	.122±.004	.147±.007	.132±.001	.138±.001	.140±.003	.140±.007
7/17/79	.068±.006	.108±.021	.168±.009	.082±.025	.084±.007	.104±.002	.150±.005	-
8/21/79	.113±.010	.102±.003	.168±.005	.133±.018	.110±.014	.313±.020	.114±.008	-
9/07/79	-	-	-	.066±.001	.083±.004**	-	-	.094±.001

*Standard deviation

**Sampled at 3 meters

phosphorus in both years; however, nitrogen limitation was extreme in 1979. If other essential nutrients were adequate, the nitrogen: to phosphorus ratio would strongly favor nitrogen fixing cyanobacteria rather than green algae and diatoms.

The total nitrogen (organic and ammonium) was determined in bottom samples collected from both reservoirs (Table 23). Bottom samples from Station 1, near the dam at Cochiti Reservoir contained more nitrogen than samples from stations 2 or 3. Bottom samples from Abiquiu Reservoir sampled on September 4, 1978 did not vary between locations. Samples collected from Station 3 at Abiquiu Reservoir on November 21, 1978 contained less nitrogen than did samples from this site on September 4, 1978; however, at Station 4 nitrogen did not vary between the two sampling dates. The bottom samples from both reservoirs contained only very small amounts of nitrogen and are probably ineffective in releasing significant amounts of nitrogen to these aquatic ecosystems.

Iron levels

Total and dissolved iron were determined in samples from Abiquiu Reservoir in the spring and summer of 1979 (Table 25). The total iron was somewhat higher on May 24, 1979 than on other sampling dates. This date corresponds to a date of rapid filling of the reservoir and the greatest amount of suspended sediments as estimated by the Secchi disk transparency measurements (Table 5). The total iron concentration tended to be greater at 5 m than at the surface in all samples; however, it did not vary appreciably between the stations sampled. The dissolved iron concentration was also highest on May 24, 1979 when it accounted for the major amount of iron in most samples. On other sampling dates, the dissolved iron ranged

Table 23. Orthophosphate concentration in membrane-filtered Cochiti Reservoir water as mg phosphorus/liter.

	STATION 1			STATION 2		STATION 3		OUTLET
Date	Surface	5m	20m	Surface	5m	Surface	5m	
3/9/78	0.030	0.032	0.040	0.033	0.033	0.024	0.030	0.038
7/6/78	0.009	0.009	0.018	0.013	0.011	0.012	0.016	0.013
8/3/78	0.012	0.020	0.028	0.008	0	0.018	0.016	0.014
8/10/78	0.020	0.018	0.040	0.022	0.024	-	-	-
8/17/78	0.006	0.008	0.024	0.010	0.018	0.010	0.008	0.031
8/29/78	0.009	0.009	0.035	0.004	0.005	-	-	0.037
9/7/78	0.006	0.003	0.024	0	0.004	0.004	0.004	-
9/28/78	0.005	0.010	0.012	0.009	0	0	0	0.004
10/07/78	0	0	0	-	-	0	0	0
4/5/79	0.028	0.030	0.042	0.034	0.030	0.026	0.042	-
5/31/79	0.028	0.033	0.026	0.026	0.038	0.057	0.033	0.033
6/19/79	0.031	0.029	0.041	0.035	0.031	0.031	0.035	0.025
7/17/79	0.025	0.021	0.042	0.023	0.017	0.017	0.027	-
8/21/79	0.038	-	0.030	0.038	0.038	0.024	0.024	-

Table 24. Total nitrogen (organic and ammonium) and organic carbon content of bottom samples from Cochiti and Abiquiu reservoirs*

Reservoir	Date	Station	Nitrogen mg N/g	Organic Carbon mg C/g
Cochiti	4/05/79	1**	1.82 ± .089†	10.82 ± .73
		2††	1.40 ± .007	12.80 ± .57
		3††	1.35 ± .071	13.95 ± .64
Abiquiu	9/04/78	2	1.16 ± .021	11.85 ± .07
		3	1.04 ± .021	8.88 ± .11
		4	1.09 ± .014	12.60 ± .85
Abiquiu	11/21/78	3	0.67 ± .071	--
		4	1.12 ± .028	--

*Duplicate determinations were conducted on each bottom sample. Except where otherwise indicated, a single bottom sample was analyzed from each station.

**Three bottom samples analyzed. Standard deviation computed between sample means.

†Standard deviation.

††Two bottom samples analyzed. Standard deviation computed between sample means.

from 0.022 to 0.161 mg/liter and on the average comprised 6.5 to 23% of the total iron concentration.

Total and dissolved iron concentration in inlet and outlet water samples from Abiquiu Reservoir are reported in Table 26. Large variations in the total iron in the inlet water is related in a general manner to variations in flow rate and, consequently, sediment load. This general trend is apparent for the total iron in the outlet water also; however; flow rates at the outlet were less variable than at the inlet. Dissolved iron increased with the total iron concentration and on the average accounts for 6% and 13.5% of the total iron in the inlet and outlet samples, respectively.

Total and dissolved zinc, copper, and manganese concentrations were determined by atomic absorption in inlet and outlet samples collected May 15, 1979 using the same samples prepared for iron analysis. The inlet and outlet samples contained the following concentrations of these essential micronutrients in mg/liter (nd = not detectible):

	Zinc		Copper		Manganese	
	Total	Dissolved	Total	Dissolved	Total	Dissolved
Inlet	0.017	0.006 $\pm$ .002	0.005	nd	0.070	0.006 $\pm$ .002
Outlet	0.012	0.007 $\pm$ .001	nd	nd	0.035	0.005 $\pm$ .004

While dissolved copper was below detectable limits, it seems unlikely that copper was limiting to phytoplankton populations. Gerloff (1975) was unable to demonstrate a copper requirement for phytoplankton species and aquatic angiosperms studied in the laboratory and concluded that aquatic plants required lower concentrations of copper than terrestrial plants.

Table 25. Total and dissolved iron concentrations in Abiquiu Reservoir water samples in mg/liter.

Date	Station	Depth	Total Fe*	Dissolved Fe**
5/24/79	2	Surface	0.758	0.642 ± .025***
		5 m	1.065	1.000 ± .003
	4	Surface	0.638	0.482 ± .037
		5 m	1.76	0.644 ± .461
6/06/79	2	Surface	0.405	0.022 ± .014
		5 m	0.520	0.056 ± .006
	3	Surface	0.532	0.042 ± .019
		5 m	1.112	0.050 ± .031
6/13/79	2	Surface	0.452	0.032 ± .019
		5 m	0.558	0.070 ± .007
	3	Surface	0.572	0.054 ± .012
		5 m	1.150	0.054 ± .016
7/10/79	2	Surface	0.568	0.138 ± 0
		5 m	0.620	0.138 ± .028
	3	Surface	0.375	0.156 ± .008
		5 m	0.525	0.045 ± .014
	4	Surface	0.378	0.070 ± .021
		5 m	0.618	0.161 ± .016

*N = 1

**Duplicate samples were prepared from portions of each total iron sample.

***Standard deviation

Table 26. Total and dissolved iron concentrations in inlet and outlet water samples from Abiquiu Reservoir in mg/liter*.

Date	Inlet		Inlet	
	Total Fe	Dissolved Fe	Total Fe	Dissolved Fe
2/27/79	2.11	0.074 ± .012**	0.838	0.070 ± .003
3/16/79	--	0.041 ± .015†	--	0.126 ± .012
4/03/79	3.42	0.092 ± .014	0.742	0.202 ± .080
4/19/79	12.90	0.187 ± .035	1.562	0.092 ± .023
5/15/79	3.34	0.320 ± 0	2.84	0.508 ± .258
6/06/79	20.41	1.039 ± .737	8.68	0.813 ± .262
7/10/79	0.920	0.112 ± .046	2.07	0.250 ± .025

*N = 1 for total iron, N = 2 for dissolved iron (subsamples)

**Standard deviation

†N = 3

Maximum total iron concentrations were found in Cochiti Reservoir on May 31, 1979 (Table 27) when Secchi disk visibility was minimal (Table 4) as a result of the high sediment load during this period of rapid filling of the reservoir. Total iron concentrations decreased greatly in June and mid-July samplings as the volume of water stored increased to nearly maximum on June 19 and inflow had already begun to decrease. Secchi disk values indicated a considerable decrease in the suspended sediment load in June and July, correlating with decreases in the particulate associated iron. In late July and early August, a slight increase in total iron occurred although the sediment load had decreased considerably according to the Secchi disk values for mid-July (Table 4).

The dissolved iron concentration was highest on May 31, 1979 when total iron concentrations were maximum (Table 27). The dissolved iron concentration decreased somewhat in June, was quite low on July 26, 1979, but increased substantially on August 1, 1979. The dissolved iron concentrations averaged 10-24% of the total iron on all sampling dates except the last date, August 1, 1979, when it increased to 60% of the total iron.

Wetzel (1975) states that dissolved iron concentrations in lakes with a pH of 5 to 8 typically range from 0.050-0.200 mg/liter while in hard water lakes (calcareous drainage areas), the dissolved iron may be as low as 0.005 mg/liter. Most dissolved iron in lakes is in the form of complexes rather than ionic iron. Our measurements of dissolved iron always were above those characteristic of hard water lakes, implying the presence of complexing agents which prevented the precipitation of insoluble $Fe(OH)_3$. Humic substances were present in inadequate concentrations to account for significant complexing of iron. On August 1, 1979 the increase in dissolved

Table 27. Total and dissolved iron concentrations in Cochiti Reservoir water samples in mg/liter.

	Station	Depth	Total Fe*	Dissolved Fe**
4/05/79	1	5 m	0.558	0.096 ± .016***
		20 m	2.23	0.165 ± .042
	2	Surface	0.435	0.077 ± .021
		5 m	0.608	0.105 ± 0
	3	Surface	0.658	0.136 ± .119
		5 m	1.63	0.120 ± .042
5/31/79	1	Surface	7.14	1.256 ± .190
		2 m	4.94	.074 ± .105
	2	Surface	4.24	0.289 ± .027
		5 m	5.74	1.072 ± .032
	3	Surface	6.89	0.425
		2 m	6.49	0.354 ± .059
6/19/79	1	Surface	1.052	0.122 ± .173
		5 m	0.892	0.425 ± .170
	2	Surface	0.885	0.129 ± .001
		5 m	0.788	0.132 ± .004
	3	Surface	1.552	0.369 ± .182
		5 m	0.328	0.137 ± .021
7/17/79	1	5 m	0.138	--
	2	Surface	0.162	--
		5 m	0.160	--
	3	5 m	0.218	--
7/26/79	2	Surface	0.492 ± .042	0.072 ± .017
8/1/79	2	Surface	0.382	0.231 ± .001

*N = 1 except on 7/26/79 when four replicate samples were analyzed

**Duplicate samples were prepared from portions of each total iron sample, except the surface sample at Station 3 on 5/31/79 which was not replicated

***Standard deviation

iron occurred as numbers of Aphanizomenon increased leading to cyanobacterial blooms in late August and September. It is possible that production of iron chelators (siderophores) by Aphanizomenon, as proposed by Murphy et al. (1976), are responsible for the increase in soluble iron concentration which would then provide adequate available iron for development of large populations of cyanobacteria. Factors other than cyanobacterial production of chelating agents are responsible for the high concentrations of dissolved iron associated with the high total iron concentrations measured when spring run-off had a maximum impact on the sediment load in both Abiquiu and Cochiti Reservoirs in May 1979.

Total iron in the inlet water from the Rio Grande above Cochiti Reservoir tended to increase with flow rate during the heavy run-off from April through July 1979 (Table 28). One extremely high total iron value obtained on March 16, 1979 was possibly due to contamination with soil. The highest total iron concentration for the April-July samples was measured on April 17, 1979 as run-off first became rapid. Subsequent samples had much lower total iron concentrations and appeared to vary with flow rate on the average, 9% of the total iron was present as dissolved iron.

The total iron concentration in the outlet water increased as flow from the outlet increased in April-June and then declined on July 10, 1979 although flow at the outlet remained at a constant high level (Table 28). The average of the total iron that was in the dissolved state was 18.5% (excluding one sample that was 100% dissolved iron). Factors increasing the percentage of dissolved iron in the outlet water compared to inlet or reservoir water may have included a limited oxygen supply at the depth of

Table 28. Total and dissolved iron concentrations in inlet and outlet water samples from Cochiti Reservoir in mg/liter*.

Date	Inlet		Outlet	
	Total Fe	Dissolved Fe	Total Fe	Dissolved Fe
2/27/79	1.872	0.115 ± .014**	0.27	0.062 ± 0
3/16/79	122.9	0.060†	0.035	0.048 ± .009
4/03/79	1.962	0.211 ± .016	0.638	0.090†
4/05/79	--	1.262 ± .009	--	0.174 ± .012
4/19/79	17.55	--	1.21	--
5/15/79	4.11	0.847 ± .672	2.20	0.288 ± .018
6/06/79	7.68	0.792 ± .387	5.18	1.258 ± .603
7/10/79	3.94	0.228 ± .060	0.692	0.126 ± .008

*N = 1 for total iron; N = 2 for dissolved iron (subsamples)

**Standard deviation

†N = 1

the outlet and reduction of ferric iron to the more soluble ferrous form as well as complex formation.

Zinc, copper, and manganese in addition to iron were determined on samples collected from the Cochiti Reservoir inlet and outlet on May 15, 1979 and results are listed in mg/liter (nd = not detectable):

	Zinc		Copper		Manganese	
	Total	Dissolved	Total	Dissolved	Total	Dissolved
Inlet	0.017	0.012 ± .004	0.010	nd	0.162	0.016 ± .002
Outlet	0.014	0.006 ± .003	0.020	nd	0.088	0.006 ± .002

As observed for the Abiquiu Reservoir inlet and outlet samples, dissolved copper was below detectable limits. The analyses suggest that these micronutrient elements are probably present in adequate concentrations for phytoplankton populations in both reservoirs.

Cation and anion analyses of Cochiti Reservoir water in March 1978 and during the heavy spring run-off in June 1979 are listed in Table 30. Water storage in Cochiti Reservoir was approximately 47,500 acre-feet in early March (estimated from late February values) and 149,200 acre-feet on June 19, 1979. During this time calcium and magnesium concentrations decreased to about 50% and sodium and sulfate concentrations decreased to 30-35% of the March 1978 concentrations. Potassium concentrations decreased slightly and the chloride concentration did not change. The concentration of cations and anions in reservoir water are quite similar to their concentration in the inlet sample from the Rio Grande. The outlet sample, with the exception of the sulfate concentration, is also very similar in composition to the reservoir water samples, indicating that Cochiti Reservoir water was well mixed between the inlet and outlet. The much more rapid release of water

Table 29. Cation and anion concentrations in membrane filtered Abiquiu Reservoir water samples in mg/liter.

Date	Station	Depth	Ca	Mg	Na	K	Cl	SO_4	Conduct*
4/04/78	2	Surface	64.7	13.3	33.3	3.08	6.22	22.0	-
		5m	66.5	14.1	36.3	3.10	6.22	17.2	-
		20m	75.0	17.2	50.8	3.45	7.72	25.0	-
	3	Surface	68.3	14.5	37.7	3.27	6.77	19.5	-
		5m	67.4	14.5	39.2	3.12	6.57	20.0	-
	4	Surface	74.8	16.9	43.4	3.49	7.12	23.7	-
		5m	75.1	17.2	43.5	3.49	7.48	24.5	-
	Outlet	-	-	-	-	-	8.42	25.8	-
11/21/78**	2	Surface	45.6	9.4	20.8	2.40	4.24	109	-
		20m	48.6	10.0	24.6	2.46	5.06	100	-
	4	Surface	45.6	9.4	20.8	2.38	4.28	104	-
		5m	46.4	9.6	21.0	2.39	4.28	104	-
6/12/79	2	Surface	28.7	5.9	8.9	1.90	4.8	42	0.19
		5m	27.5	5.8	8.3	1.85	1.9	38	0.18
		20m	23.4	3.8	6.5	1.34	3.1	30	0.15
	3	Surface	28.4	6.0	7.3	1.86	2.7	40	0.21
		5m	28.	5.9	7.9	1.88	3.2	36	0.20
	4	Surface	29.3	5.8	7.3	1.83	2.8	36	0.18
		5m	28.7	5.5	8.2	1.76	2.2	30	0.18
	Outlet		18.6	3.15	3.0	1.44	0.8	26	
	Inlet		13.9	1.95	7.0	1.13	3.4	12	

*Conductivity in mmhos/cm

**Most samples collected on 4/04/78 and 11/21/78 contained concentrations of the following cations below detectable limits by the standard atomic absorption analysis: Fe (< .03 mg/liter), Mn (< .02 mg/liter), Cu (< .01 mg/liter), Zn (< .001 mg/liter). On 4/08/78 zinc concentrations in samples from Station 2 at 20 and Station 3 at surface were 0.001 and 0.004 mg/liter respectively. On 11/21/78 manganese concentration in samples from Station 2 at 20 was 0.02 mg/liter.

Table 30. Cation and anion concentrations in membrane filtered Cochiti Reservoir water samples in mg/liter

Date	Station	Depth	Ca	Mg	Na	K	Cl	SO_4	Conduct**
3/09/78	1	Surface	34.9	6.8	22.2	2.97	7.5	56.3	0.320
		5m	35.3	6.9	22.4	2.97	7.8	55.3	0.335
		20m	38.2	7.4	23.7	3.05	8.3	63.7	-
	2	Surface	35.6	7.0	22.1	2.88	7.2	62.1	0.343
		5m	35.1	6.9	22.0	2.88	7.8	57.1	0.289
	3	Surface	39.4	7.9	23.1	2.99	7.5	75.8	0.349
		5m	36.9	7.4	21.6	2.82	7.5	74.7	0.353
	Outlet		36.8	7.1	23.4	3.06	7.9	57.9	-
6/19/79	1	Surface	20.1	3.05	7.0	2.35	11.7	22	-
		5m	17.4	2.75	8.6	2.36	6.0	18	-
		20m	22.1	3.45	8.6	2.37	7.4	22	-
	2	Surface	18.1	2.75	7.7	2.30	6.0	22	-
		5m	15.7	2.45	8.1	2.33	4.7	24	-
	3	Surface	19.3	2.85	8.4	2.35	8.0	20	-
		5m	17.1	2.55	7.8	2.36	5.5	18	-
	Outlet		22.2	3.25	7.9	2.43	5.6	38	-
	Inlet		15.4	2.45	7.6	2.13	8.0	22	-

*All samples collected on 3/09/78 contained concentrations of the following cations below detectable limits by the standard atomic absorption analysis: Fe (< 0.03 mg/liter), Mn ($<$ .02 mg/liter), Cu ($<$ .01 mg/liter), Zn($<$ .001 mg/liter).

**Conductivity in mmhos/cm.

from Cochiti than Abiquiu Reservoir probably is responsible for the differences in degree of mixing in the two reservoirs.

Both reservoirs are rich in calcium and sulfate ions; however, substantial variations in ionic concentrations occurred depending on the rate of inflow. As typical of North American river waters (Wetzel, 1975), the relative abundance of the major ions in both reservoirs was Ca > Na > Mg > K and SO_4 >> Cl. These ions are probably always present in adequate concentrations for phytoplankton or macrophytic growth in both reservoirs.

Animal toxicity of phytoplankton

Floating mats of cyanobacteria were collected annually from each reservoir at the peak of the phytoplankton bloom. The cyanobacteria, about 95% Aphanizomenon flos-aquae, were found to be toxic to mice when the macerated cells were injected intraperitoneally. When tested with protozoans, these extracts from Aph. flos-aquae were also markedly toxic to Paramecium caudotum but not to Stentor sp. nor to Vorticella sp. Hourly examination of the protozoans after dilutions of Aph. flos-aquae extract were added demonstrated death and lysis of P. caudatum. Although this protozoan sensitivity could be used to assay cyanobacterial toxin, the inherent problems of handling the protozoans led us to pursue other sensitive tests. Our establishment of a white-cell toxicity assay for Aph. flos-aquae has great possibilities in aquatic biology since this method is far more sensitive than the mouse-toxicity assay (Barton, et al., 1980).

Phytoplankton studies

Results of phytoplankton identification and enumeration in samples from Abiquiu Reservoir are given in Table 31. Aphanizomenon was the dominant phytoplankton from July-November 1978. Appreciable numbers of Anabaena

occurred with Aphanizomenon at all stations on July 19, 1978 and at two stations on August 4, 1978. Microcystis, a non-nitrogen fixing cyanobacterium, which produces nuisance blooms elsewhere in the United States, was found in small numbers on August 4, 1978. Aphanizomenon populations reached bloom proportions (over 100,000 cells/ml) at Station 4 on August 4, 1978 and at Station 3 on September 14, 1978. The number of Aphanizomenon decreased greatly by November 21, 1978 although it remained the dominant phytoplankton. Aphanizomenon cells were almost invariably more abundant in surface samples than at the 2 m depth. In July and August, Aphanizomenon filaments with heterocysts far exceeded non heterocyst filaments; however, when populations were maximum in September, filaments without heterocysts were more abundant than those with heterocysts. Small numbers of the cyanobacterium Gloeocystis occurred in samples collected from July-November 1978.

In April and May 1979, phytoplankton numbers were low; however, Gloeocystis was the most abundant phytoplankton. Small populations of Aphanizomenon were noted in June and increased to a maximum number of 42,700 cells/ml on July 10, 1979. By the last sampling date, August 9, 1979, Aphanizomenon populations had greatly declined. The Aphanizomenon filaments predominantly included heterocysts only in the July 10 sampling in 1979. Small numbers of Schroederia occurred in samples collected from May-August. Phytoplankton populations were much lower in 1979 than 1978 and did not reach bloom proportions during the 1979 sampling period.

Analysis of selected cations and anions

The data in Table 29 indicate the variation in the concentration of the major cations and anions in Abiquiu Reservoir water which occurred in a year

Table 31. Identification and enumeration of phytoplankton collected from Abiquiu Reservoir.

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
04/04/78	2-S	Aphanizomenon	2,222	0			
	2-2	Actinastrum	256				
	3-S	nd*					
	3-2	nd*					
	4-S	nd*					
	4-2	Aphanromenon	1,792	0			
07/19/78	1-S	Aphanizomenon	62,643	3,684	20	55,263	7,380
		Anabaena	15,783	1,052	10	5,263	10,520
	1-2	Aphanizomenon	27,625	769	25	8,400	19,225
		Anabaena	7,680	512	15		7,680
	2-S	Ceratium	256				
		Aphanizomenon	20,508	769	20	5,128	15,380
		Anabaena	3,078	513	6		3,078
	2-2	Aphanizomenon	13,180	512	15	5.500	7,680
		Ceratium	256				
		Anabaena	2,560	256	10		2,560
	3-S	Aphanizomenon	41,872	1,256	18	19,102	22,770
		Anabaena	6,578	506	13		6,578
	3-2	Ceratium	201				
		Anabaena	804	0			
		Aphanizomenon	16,080	804	10	8,040	8,040
07/26/78	2-S	Aphanizomenon	49,529	1,342	24	17,321	32,208
	2-2	Aphanizomenon	32,086	263	30	24,196	7,890
	3-S	Aphanizomenon	45,929	1,435	22	14,359	31,570
		Staurestrum	1,230	0			
	3-2	Aphanizomenon	24,196	789	20	8,416	15,780
		Diatoma	526				
	4-S	Aphanizomenon	35,454	1,866	19		35,484
		Gloeocystis	266				
	4-2	Gloeocystis	779				
		Aphanizomenon	17,394	779	15	5,709	11,685
08/04/78	2-S	Aphanizomenon	79,588	1,616	28	34,340	48,248
		Anabaena	404	0			
	2-2	Aphanizomenon	50,202	1,569	26	9,408	40,794
	3-S	Aphanizomenon	70,434	2,174	18	31,302	39,132
		Anabaena	4,785	957	5		4,785
		Hantzchia	217				
		Microcystis	652				
	3-2	Aphanizomenon	72,000	2,000	23	26,000	46,000
		Microcystis	400				
		Gloeocystis	400				
	4-S	Aphanizomenon	102,812	2,690	29	24,792	78,020
		Microcystis	563				
	4-2	Aphanizomenon	45,374	1,538	22	11,538	33,836
		Microcystis	1,154				

*nd = not detectable

Table 31. (Continued)

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
09/14/78	2-S	Aphanizomenon	83,783	755	45	49,808	33,975
		Ceratium	252				
	2-2	Aphanizomenon	72,360	804	45	36,180	36,180
		Gloeocystis	201				
	3-S	Aphanizomenon	150,115	1,772	23	109,359	40,756
	3-2	Aphanizomenon	118,520	740	25	100,000	18,520
	4-S	Aphanizomenon	734	0		734	
	4-S	Aphanizomenon	12,903	253	21	7,590	5,313
11/21/78	2-S	Gloeocystis	394				
	2-2	Aphanizomenon	3,662	0			
		Gloeocystis	282				
	3-S	Aphanizomenon	13,207	269	29	5,391	7,816
	3-2	Aphanizomenon	7,567	270	20	2,162	5,405
	4-S	Aphanizomenon	23,066	869	23	20,000	3,066
	4-2	Aphanizomenon	6,760			6,760	
04/20/79	2-S	nd*					
	2-2	nd*					
	3-S	nd*					
	3-2	Gloeocystis	267				
05/24/79	2-S	Gloeocystis	523				
	2-2	Gloeocystis	308				
		Schroederia	308				
	3-S	Gloeocystis	845				
	3-2	nd*					
	4-S	Schroederia	267				
		Gloeocystis	534				
	4-2	nd*					
06/12/79	2-S	Schroederia	388				
	2-2	Aphanizomenon	1,875	0			
06/19/79	3-S	Gloeocystis	256				
	3-2	nd*					
	4-S	Aphanizomenon	2,264	0			
	4-2	nd*					
07/10/79	2-S	Aphanizomenon	42,702	8,108	30	2,162	40,540
	2-2	Aphanizomenon	2,837	283	10		2,837
	3-S	Aphanizomenon	9,076	179	22	5,128	3,948
		Anabaena	4,872	256	19		4,872
	3-2	Aphanizomenon	21,539	1,025	17	4,103	17,436
		Anabaena	12,521	512	25		
	4-S	Aphanizomenon	8,462	512	12	2,308	6,154
		Schroederia	769				
	4-2	Schroederia	1,538				
		Aphanizomenon	2,307	256	9		

*nd = not detectable

Table 31. (Continued)

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
08/09/79	2-S	nd*					
	2-2	Aphanizomenon	784	0			
	3-S	Schroederia	258				
		Microcystis	258				
	3-2	Aphanizomenon	6,202	0			
	4-S	Aphanizomenon	3,200	0			
	4-2	nd*					

*nd = not detectable

of below average run-off (1978). At the time of the April and November samplings in 1978, water storage was 19,000 and 17,000 acre-feet, respectively. The concentration of calcium, magnesium, sodium, potassium, and chloride all decreased by about one-third between the spring and fall samplings. In contrast, sulfate increased by a factor of 4-5 during this time period.

During the unusually heavy run-off in the spring of 1979, all ions listed in Table 29 decreased markedly as water storage increased to 135,140 acre-feet on June 12, 1979. Calcium, magnesium, potassium, and chloride concentrations decreased by 30-40% while sodium and sulfate decreased by 50-70%. While the ion concentrations in the Chama River would vary with time, the low concentrations of these ions in the one inlet sample analyzed indicated that it would effectively dilute the major cations and anions in the reservoir water. Because of the unusually great snowpack in 1979, concentrations in inlet water would be expected to be more dilute than in years of average run-off.

Ion concentrations in water sampled at the outlet on June 12, 1979 are lower than in samples from surface, 5 m or 20 m depths at Station 2 which is close to the outlet, as well as samples collected elsewhere in the reservoir. This suggests that cold water was flowing from the inlet along the bottom of the reservoir to the outlet with only limited mixing with the warmer water above.

A rather large diversity of phytoplankton genera were identified in samples collected from Cochiti Reservoir in March through July of 1978 (Table 32). While the cyanobacteria Aphanizomenon and Microcystis occurred in these samples, their numbers were small. Aphanizomenon and Anabaena

increased in numbers in August and were the most abundant phytoplankton in most samples. On September 7, 1978, Anabaena and Aphanizomenon were both present in numbers of 10,000-30,000 cells/ml; however, by late September Aphanizomenon, with up to 72,000 cells/ml, was far more abundant than Anabaena. On October 6, 1978, Aphanizomenon populations were even greater and at Station 3 had attained bloom proportions (187,000 cells/ml). Most filaments of Aphanizomenon and Anabaena included a heterocyst. Small numbers of Gloeocystis occurred in most of the cyanobacteria dominated samples collected in September and October.

Only Gloeocystis occurred in samples collected on April 5, 1979. During the period of most rapid filling in June 1979, phytoplankton were not observed in most samples. In samples collected on July 17, 1979, relatively small numbers of Aphanizomenon were observed; however, no other genera were found. On August 21, 1979, an Aphanizomenon bloom (212,000 cells/ml) occurred at Station 3. The only other genus noted was Anabaena which also was found at Station 3. An Aphanizomenon bloom occurred at Station 1, 2, and 3 on September 7, 1979. Aphanizomenon was the only genus observed in samples from Stations 1 and 3, while small numbers of Anabaena were collected at Station 2 (see also Table 54).

In 1978, a year of below average run-off, Aphanizomenon populations approached bloom magnitude in Abiquiu Reservoir in early August and September while in Cochiti Reservoir blooms began to develop in late September and October. In 1979, a year of extremely high run-off, only small populations of Aphanizomenon appeared in Abiquiu Reservoir while blooms of this organism occurred in Cochiti Reservoir in August and September. The occurrence of phytoplankton genera in Abiquiu and Cochiti

Table 32. Identification and enumeration of phytoplankton collected from Cochiti Reservoir.

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
03/09/78	1-S	Actinastrum	645				
	1-2	Closteridium	285				
		Actinastrum	286				
	2-S	Diatoma	266				
		Actinastrum	267				
		Opephora	267				
	2-2	Actinastrum	270				
		Diatoma	540				
	3-S	Diatoma	1,644				
		Aphanizomenon	1,365	0			
		Akistrodesmus	273				
	3-2	Actinastrum	256				
		Akistrodesmus	256				
		Diatoma	256				
05/18/78	1-S	Actinastrum	1,013				
		Diatoma	253				
		Microcystis	253				
	1-2	Actinastrum	755				
		Staurastrum	377				
		Diatoma	755				
	2-S	Actinastrum	444				
		Aphanizomenon	1,332				
	2-2	Staurastrum	312				
		Actinastrum	312				
	3-S	Microcystis	256				
		Actinastrum	128				
		Akistrudesmus	256				
06/13/78	1-S	Diatoma	247				
	1-2	Anabaena	200	0			
		Microcystis	200				
	2-S	Microcystis	250				
	2-2	Navicula	253				
	3-S	Akistrodesmus	741				
		Aphanizomemon	247	0			
		Diatoma	247				
	3-2	Akistrodesmus	253				
		Diatoma	253				
07/06/78	1-S	Akistrodesmus	258				
	1-2	Asterionella	267				
	2-S	Diatoma	263				
		Microcystis	132				
	2-2	Ankistrodesmus	519				
		Microcystis	1,818				
	3-S	Schroederia	202				
	3-2	Pediastrum	260				
		Akistrodesmus	260				
		Denticula	260				

Table 32 (continued)

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
08/03/78	1-S	Diatoma	3,402				
		Microcystis	253				
		Aphanizomenon	5,060	253	20		5,060
	2-S	Diatoma	2,322				
		Anabaena	1,290	0			
	2-S	Anabaena	615	0			
		Diatoma	1,236				
	3-S	Microcystis	790				
		Aphanizomenon	18,954	526	18	9,477	9,477
	3-2	Microcystis	263				
		Aphanizomenon					
08/10/78	1-S	Diatoma	2,952				
		Pahanizomenon	2,624	287	8	328	2,296
	1-2	Diatoma	1,088				
		Microcystis	272				
		Anabaena	4,896	273	18		4,896
	2-S	Anabaena	3,708	412	9		3,708
	2-2	Microcystis	253				
		Pediastrum	253				
08/17/78	1-S	Aphanizomenon	4,576	286	16		4,576
		Anabaena	2,288	286	8		2,288
		Microcystis	286				
	1-2	Aphanizomenon	4,620	308	15		4,620
		Anabaena	2,156	308	7		2,156
	2-S	Microcystis	260				
	2-2	Aphanizomenon	6,890	265	26		6,890
		Microcystis	530				
	3-5	Aphanizomenon	9,468	526	18		9,468
		Anabaena	1,578	0			
		Gloeocystis	263				
	3-2	Gloeocystis	804				
		Aphanizomenon	3,216	201	16		3,216
		Ceratium	201				
08/29/78	1-S	Aphanizomenon	20,520	1,026	20		
		Anabaena	4,617	513	9		
		Diatoma	1,280				
		Gloeocystis	256				
	1-2	Cloeocystis	1,019				
		Aphanizomenon	6,112	764	8		
		Anabaena	1,785	255	7		
	2-S	Aphanizomenon	8,658	255	20	6,108	2,550
		Anabaena	3,054	509	6		
	2-2	Anabaena	6,312	789	8		
		Aphanizomenon	9,468	526	15	1,578	7,890
		Denticula	263				

Table 32. (continued)

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
09/07/78	1-S	Anabaena	10,696	764	14		10,696
		Aphanizomenon	25,232	510	30	9,932	15,300
		Gloeocystis	510				
	1-2	Aphanizomenon	5,920	370	16		5,920
		Anabaena	3,333				
		Gloeocystis	370				
	2-S	Anabaena	20,209	1,429	12	3,061	17,148
		Aphanizomenon	17,544	408	23	8,160	9,384
		Gloeocystis	408				
	2-2	Pedastrium	250				
		Gloeocystis	500				
		Anabaena	9,000	750	12		9,000
		Aphanizomenon	8,000	250	25	1,750	6,250
	3-S	Anabaena	25,915	1,258	19	2,013	23,902
		Aphanizomenon	12,327	503	14	5,285	7,042
	3-2	Anabaena	22,635	1,509	15		22,635
		Aphanizomenon	29,065	755	30	6,415	22,650
		Gloeocystis	377				
		Diatoma	1,509				
09/28/78	1-S	Aphanizomenon	44,598	1,538	27	3,072	41,526
		Anabaena	2,048	256	8		
	1-2	Aphanizomenon	27,462	762	25		
		Gloeocystis	381				
	2-S	Cloeocystis	769				
		Aphanizomenon	10,766	0			
	2-2	Gloeocystis	2,280				
		Aphanizomenon	1,656	0			
		Anabaena	1,449	0			
	3-S	Aphanizomenon	71,939	1,818	21	33,761	38,178
		Gloeocystis	779				
		Denticula	260				
10/06/78	1-S	Aphanizomenon	40,014	1,053	29	9,477	30,537
		Gloeocystis	526				
	1-2	Aphanizomenon	42,641	1,132	33	5,285	37,356
		Gloeocystis	377				
	2-S	Aphanizomenon	20,640	516	27	6,708	13,932
	3-S	Aphanizomenon	187,010	2,857	26	112,728	74,282
		Anabaena	3,117	0			
		Gloeocystis	2,597				
		Denticula	519				
	3-2	Aphanizomenon	54,215	1,579	21	21,056	33,159
		Gloeocystis	2,632				
	2-S	Aphanizomenon	20,640	516	27	6,708	13,932

Table 32. (continued)

Date	STATION-DEPTH(m)	GENUS	TOTAL CELLS/ml	CYANOPHYTES			
				Heterocysts/ml	Cells/heterocyst	Filaments/ml	
						w/o heterocysts	w/heterocysts
04/05/79	1-S	Gloeocystis	264				
	1-2	nd*					
	2-S	Gloeocystis	292				
	2-2	Gloeocystis	630				
	3-S	Gloeocystis	274				
	3-2	nd*					
06/19/79	1-S	nd*					
	1-2	nd*					
	2-S	nd*					
	2-2	nd*					
	3-S	Schroederia	252				
07/17/79	1-S	Aphanizomenon	5,676	0			
	1-2	Aphanizomenon	2,564	0			
	3-S	Aphanizomenon	3,057	0			
	3-2	Aphanizomenon	2,532	0			
08/21/79	1-S	Aphanizomenon	4,967	261	19		4,967
	1-2	Aphanizomenon	2,308	0			
	2-2	Aphanizomenon	13,164	506	26		13,164
	3-S	Aphanizomenon	212,307	3,333	36	92,308	119,999
		Anabaena	12,308	1,538	8		12,308
09/07/79	1-S	Aphanizomenon	73,425	426	30	60,645	12,780
	1-2	Aphanizomenon	179,215	1,176	45	126.274	52,941
	3-S	Aphanizomenon	61,951	488	31	46,829	15,122
	3-2	Aphanizomenon	95,656	784	45	60,392	35,294

* nd = not detectable

reservoirs is summarized in Table 33. Both reservoirs are dominated by Aphanizomenon with Anabaena as the second most abundant genus. During this study a greater number of phytoplankton genera were observed in Cochiti than in Abiquiu Reservoir. The diversity of phytoplankton in Cochiti is attributed to samples collected in the spring and summer of 1978 when the Aphanizomenon population was small to intermediate in size. In 1979, Cochiti Reservoir was almost completely dominated by Aphanizomenon after mid-July.

Tables 34 and 35 list chlorophyll-a concentrations for Abiquiu and Cochiti Reservoirs. While chlorophyll-a concentrations for Abiquiu and Cochiti Reservoirs in general vary in proportion to the number of phytoplankton cells in preserved samples (tables 31 and 32), chlorophyll a concentrations often failed to show differences between stations and depths that are apparent in cell counts. While chlorophyll samples were stored on ice in the field and upon return to the laboratory filtered and frozen in a desiccator until extraction, degradation of chlorophyll may have been a problem with some samples. Chlorophyll a concentrations were thus a rather insensitive measure of the abundance of phytoplankton in water samples. The apparent change in chlorophyll concentration in the reservoir at different times of the day (Table 36) further suggests that correlations of chlorophyll content and trophic status of reservoirs should be done with extreme caution.

Primary productivity measurements at Abiquiu Reservoir are given in Table 37 and Fig. 7. Surface samples, incubated at a depth of 0.5 m, were probably rarely light limited and thus may be compared as an indication of seasonal variation in primary productivity of the surface water. Primary productivity was high on 5-30-78 at 140.7 and 52.4 mg carbon/m^3 hr at

Table 33. Summary of phytoplankton.

Reservoir	Organisms in greatest abundance	Organisms present in few numbers	
Cochiti	Aphanizomenon	Actinastrum	Closteridium
	Anabaena	Diatoma	Opephora
		Ankistrodesmus	Microcystis
		Staurastrum	Navicula
		Asterionella	Schroederia
		Pediastrum	Denticula
		Gloeocystis	Ceratium
Abiquiu	Apanizomenon	Actinastrum	Gloeocystis
	Anabaena	Ceratium	Hantzschia
		Staurastrum	Microcystis
		Diatoma	Schroederia

Table 34. Chlorophyll-a concentrations in Abiquiu Reservoir water as µg/liter.

	Station 2		Station 3		Station 4	
Date	Surface	2m	Surface	2m	Surface	2m
4/04/78	4.0	6.6	1.5	0.4	5.9	0
5/30/78	0	0	0	0	0	0
7/13/78	---	---	11.9	---	---	---
7/19/78	11.6	0	0	0	0	0
7/26/78	0	0	3.4	0	0.7	0
8/04/78	3.6	3.3	7.3	2.6	11.3	3.2
9/04/78	3.6	3.3	7.3	2.6	11.3	3.2
9/14/78	8.4	7.8	21.4	26.4	4.4	6.0
7/10/79	11.6	8.8(4.2)*	13.2	11.5	26.6	3.4(2.3)
8/09/79	5.3	6.8(0.5)	5.7	10.7	8.4	5.7

*Values in ( ) are phaeophytin which are indicated as being measurable only at these times.

Table 35. Chlorophyll-a concentrations in Cochiti Reservoir as µg/liter.

	Station 1		Station 2		Station 3	
Date	Surface	2m	Surface	2m	Surface	2m
3/09/78	6.8(0.4)*	13.8	10.5	7.0	4.0	3.8
5/16/78	0	0	0	8.2	0	0
6/13/78	5.4	2.3	2.5(2.9)	2.9	2.1	1.1
7/06/78	2.3	1.3(1.6)	1.8	1.5(0.3)	5.5	1.6
8/03/78	3.9	4.1(0.3)	1.6(0.5)	2.7(0.4)	0.3(4.9)	2.6
8/10/78	1.1(1.4)	3.0	3.0(0.6)	4.5	---	---
8/17/78	0.5(0.2)	0.9	0.8	2.3	3.3	2.5(0.6)
8/29/78	4.8	5.1	4.3	3.0	---	---
9/07/78	1.6(0.2)	2.6	2.7	2.9(0.2)	11.6(2.4)	3.8(0.5)
6/19/79	4.4	3.6	8.9	2.6(13.2)	1.9(8.6)	7.8(0.7)
7/17/79	3.4	4.7	3.3	3.5	6.6	7.2
7/26/79	---	---	26.2(1.5)	---	---	---
8/01/79	---	---	81.3	---	---	---
8/07/79	39.8	---	---	---	---	---
8/14/79	---	---	104.6	---	---	---
8/21/79	8.5(28.5)	4.5(2.5)	2.6(5.4)	7.7(5.9)	151.1	14.6(15.8)

*Values in ( ) are phaeophytin which are indicated as being measurable only at these times.

Table 36. Concentration of Chlorophyll in a water column at Cochiti Reservoir

Time[1]	Depth	Chlorophyll-a µg/1	Total Chlorophyll-a in Top 3 Meters (µg/4ℓ)
0600	Surface	1488.0	
	1 Meter	839.6	
	2 Meters	1167.2	
	3 Meters	655.3	4150.1
1100	Surface	860.0	
	1 Meter	1201.3	
	2 Meters	1180.8	
	3 Meters	464.1	3706.2
1400	Surface	962.4	
	1 Meter	477.8	
	2 Meters	518.7	
	3 Meters	416.3(159.7)*	2375.2
1800	Surface	-- (341.4)*	
	1 Meter	450.5	
	2 Meters	832.7	
	3 Meters	150.1(305.9)	1433.3

[1]Experiment conducted on 9/07/79 at Station 1. Time listed as Mountain Standard Time.

*Values in ( ) are phaeophytin which are indicated as being measurable only at these times.

Table 37. Primary productivity of Abiquiu Reservoir in mg carbon/m^3/hr. Values are means ± standard deviation (N = 2).

Date	STATION 2					STATION 3				
	surface	1 m	2 m	3 m	4 m	surface	1 m	2 m	3 m	4 m
5/30/78	140.74±10.93	16.40±5.71	3.10±2.74	3.60±3.41	2.45±0.57	52.39±2.24	0.91±1.29	4.11±5.41	4.88±0.86	0.00±0.00
7/19/78	33.21±2.05	1.56±2.20	-	-	-	49.51±0.51	15.88±1.45	-	-	-
7/26/78	38.25±0.54	8.82±1.19	4.74±4.01	1.67±2.02	-	60.23±15.24	12.96±2.28	0.00±0.00	1.09±0.07	-
8/4/78	16.69±1.54	10.48±5.27	0.72±0.41	0.17±0.12	0.62±0.59	53.83±13.91	9.33±5.43	1.63±0.28	0.00±0.00	0.00±0.00
9/14/78	-	-	-	-	-	129.60±10.26	15.54±2.05	2.62±1.82	2.79±0.04	3.73±1.91
11/21/78	-	-	-	-	-	12.45±0.23	8.30±0.34	0.00±0.00	0.19±0.25	1.81±2.55
5/24/79	52.72±0.86	2.20±0.22	3.00±0.29	2.14±1.95	0.66±0.93	49.04±1.36	11.56±3.78	3.36±0.57	0.78±0.19	0.88±0.28
6/12/79	8.26±0.56	6.60±0.35	2.10±0.18	0.00±0.00	-	3.45±0.45	3.02±0.22	0.73±1.03	1.06±1.21	-
7/10/79	12.04±3.85	6.20±0.24	6.70±0.32	2.10±0.04	0.72±0.17	17.51±1.40	12.02±2.51	19.13±9.50	6.45±2.05	2.78±0.01
8/09/79	7.58±0.18	5.00±1.76	3.55±0.28	1.07±0.32	0.56±0.16	-	-	-	-	-

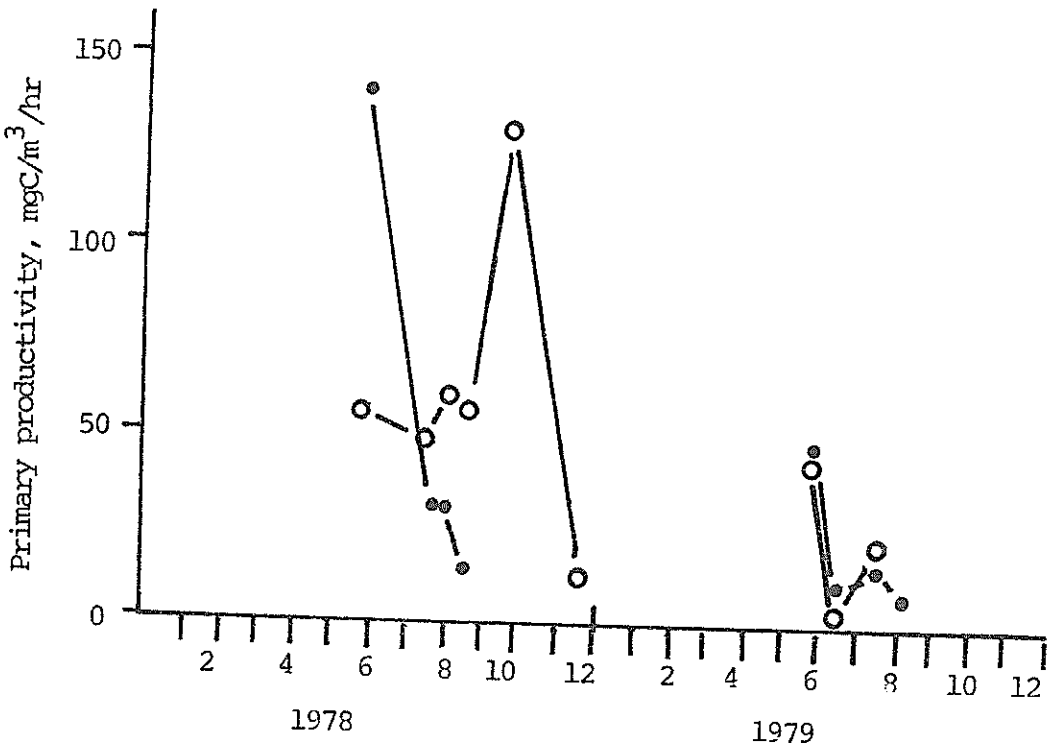

Figure 7. Carbon dioxide fixation values to calculate primary productivity of Abiquiu Reservoir. Surface levels at Station 2 (•) and Station 3 (o).

Stations 2 and 3, respectively. Primary productivity decreased at Station 2 in July and August (16.7-38.2 mg carbon/m^3 hr) while values at Station 3 were similar to the May 30, 1978 value. On September 14, 1978 an Aphanizomenon bloom occurred at Station 3 and primary productivity was quite high (129.6 mg carbon/m^3/hr). By November 21, 1978 primary productivity of surface water at Station 3 decreased to 12.4 mg carbon/m^3/hr as phytoplankton populations decreased greatly (Table 31) and as water temperature decreased from 18 to 7°C (Table 2). Primary productivity was again rather high (about 50 mg carbon/m^3 hr) at Stations 2 and 3 on May 24, 1979. Primary productivity declined to relatively low levels (3.5-17.5 mg carbon/m^3 hr) in surface samples from June-August 1979.

Primary productivity of surface samples follows trends apparent in the cell count data during the summer and fall of 1978 when Aphanizomenon and Anabaena were the dominant phytoplankton. The primary productivity of the surface water on May 24, 1979 was moderately high (50 mg carbon/m^3 hr) while phytoplankton counts were very low and included only Gloeocystis and Schroederia. The discrepancy between primary productivity and cell counts on this date suggests that the iodine settling method may have destroyed cells of some types of phytoplankton and indicated on this date a much lower phytoplankton abundance than actually occurred.

In the period of May through September 1978, light penetration was limited by either suspended sediment or phytoplankton cells as indicated by Secchi disk values of 28-48 cm (Table 4). Because cell counts were often fairly similar in surface and 2 m samples, primary productivity is inferred to be severely light limited even at the 1 m depth and very little photosynthetic activity was measured at 2 m or greater depths. Light was

limiting at 1 m on May 24, 1978; however, transparency increased as indicated by Secchi disk values of 76-200 cm in June-August 1979. Even with this increase in transparency, little photosynthetic activity was measured at a depth of 4 m.

Primary productivity measurements at Abiquiu Reservoir were higher in 1978 than reported for 1976-1977 (Barton and Johnson, 1978); however, primary productivity in 1979 was similar to the 1976-77 values. The productivity of surface water was much greater in 1978 than in other years; however, due to the limited light penetration, productivity decreased rapidly at greater depths.

Primary productivity of surface samples was probably only infrequently light limited in Cochiti Reservoir and these measurements in Table 38 and Figure 8 may be compared to obtain an estimate of the potential for productivity without light limitation throughout the study. Primary productivity of surface samples attained low to moderate levels on March 9, 1978 (16.2 and 6.6 mg carbon/m^3/hr at stations 1 and 2, respectively). Primary productivity increased to a range of 27.1-37.0 mg carbon/m^3/hr in May and June, then declined slightly in July to mid-August with a range of 13.6-25.5 mg carbon/m^3/hr). Productivity values of the surface water increased to 29.3-76.6 mg carbon/m^3/hr in late August and September when moderate numbers of cyanobacteria occurred.

Productivity was low on April 5, 1979 (6.4-7.5 mg carbon/m^3/hr at stations 1 and 2). During the period of rapid filling of Cochiti Reservoir in May and June of 1979, primary productivity of surface water remained low, ranging from 5.8-15.2 mg carbon/m^3/hr with a higher value of 31.7 mg carbon/m^3/hr on May 31, 1979 at Station 2. As a result of the heavy

Table 38. Primary productivity of Cochiti Reservoir as mg carbon /m^3/hr. Values are means ± standard deviation (N = 2).

Date	STATION 1					STATION 2				
	surface	1 m	2 m	3 m	4 m	surface	1 m	2 m	3 m	4 m
3/09/78*	16.21±7.38	22.94±3.78	11.27±1.09	2.14±0.28	2.32±1.75	6.60±0.13	2.37±0.42	14.30±16.48	1.32±0.44	0.92±0.44
5/16/78	34.11±6.42	5.28±2.18	0.43±0.61	0±0	0±0	31.02±1.90	0±0	0±0	5.78±8.18	0±0
6/13/78	27.16±26.96	7.92±0.25	1.02±1.43	0.27±0.32	2.03±2.27	37.02±0.04	5.99±0.10	3.36±2.96	2.43±0.43	0.76±0.50
7/06/78	19.70±6.54	35.52±26.73	2.72±1.70	5.62±7.94	0±0	13.59±2.46	0.15±0.22	12.86±16.50	2.30±1.43	0±0
8/03/78	18.53±0.80	19.32±2.41	14.72±2.38	5.70±0.20	2.37±0.20	20.81±0.03	21.94±3.85	14.74±1.61	6.56±0.44	6.86±2.45
8/10/78	25.46±1.97	25.75±1.54	18.91±1.01	13.55±1.70	9.49±0.64	-	-	-	-	-
8/17/78	15.60±0.47	15.99±1.72	13.10±1.06	11.73±1.64	6.18±0.29	-	-	-	-	-
8/29/78	47.99±0.34	41.08±2.77	35.36±0.38	21.88±2.35	9.62±1.33	-	-	-	-	-
9/07/78	76.62±0.26	51.23±2.21	32.77±0.90	19.03±3.86	5.66±0.97	-	-	-	-	-
9/28/78	39.00±2.54	54.88±5.09	48.04±2.69	20.19±2.87	25.96±0.38	29.34±2.01	54.43±4.26	44.14±3.02	45.72±1.36	26.21±5.10
4/05/79	7.53±0.80	11.47±0.41	4.62±0.21	1.97±0.40	0.70±0.98	6.38±0.24	9.40±1.27	1.49±0.01	0.40±0.40	0.59±0.84
5/31/79	5.76±0.74	0.00±0.00	0.80±0.52	1.22±0.76	0.07±0.10	31.66±4.63	0.30±0.17	0.52±0.32	0.00±0.00	0.60±0.28
6/19/79	15.22±4.78	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	13.56±0.35	0.00±0.00	5.16±5.59	0.34±0.49	0.00±0.00
7/17/79	44.92±2.42	27.95±9.22	9.29±1.98	4.46±3.47	2.10±0.65	22.77±0.50	23.68±4.55	6.42±2.75	0.82±1.15	0.26±0.36
8/21/79	42.92±18.74	8.04±3.84	2.28±3.23	0.00±0.00	1.09±0.26	133.81±57.13	30.05±17.11	1.22±1.73	3.20±4.52	1.52±2.16

* Station 1 at 5 m was was 1.60 ± 1.46 mg carbon/m^3/hr

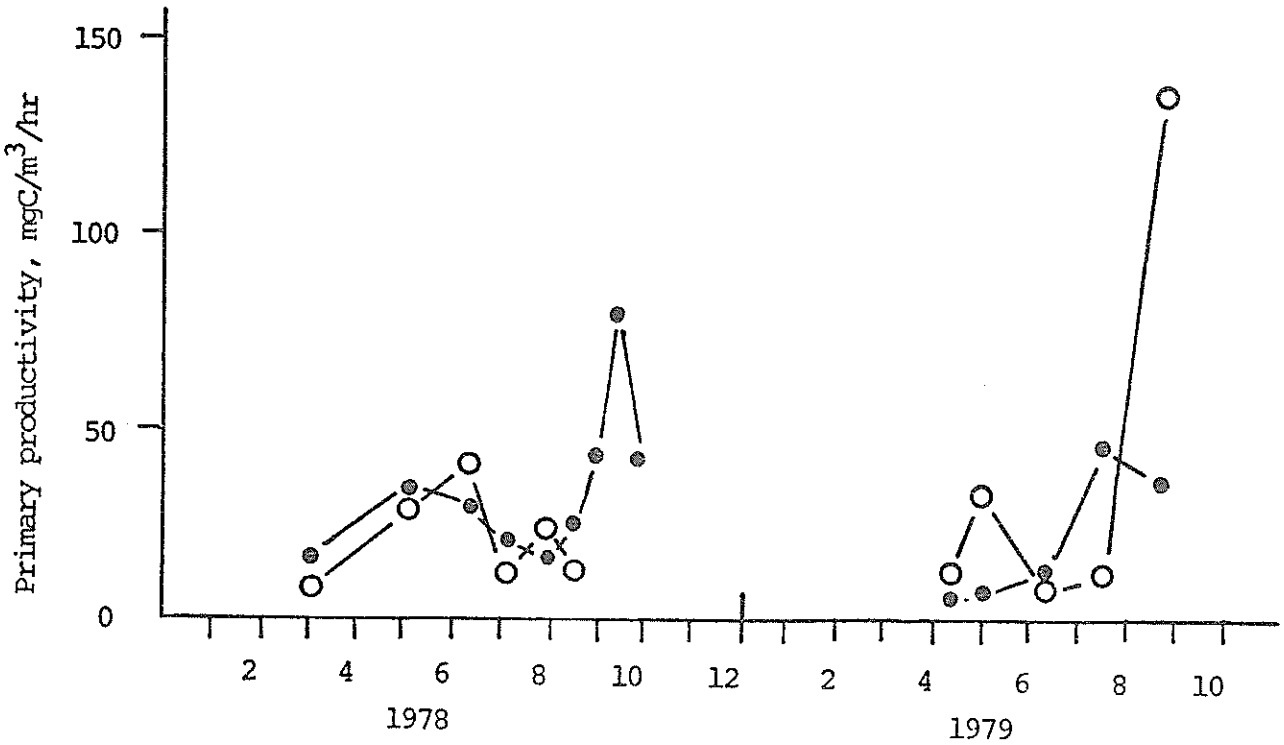

Figure 8. Carbon dioxide fixation values used to calculate primary productivity of Cochiti Reservoir. Surface levels at Station 1 (●) and Station 2 (o).

sediment load, surface samples on May 31, 1979 were probably light limited. Primary productivity increased in July and August samples with values of 44.9 and 22.7 mg carbon/m^3/hr on 7-17-79 and 42.9 and 133.8 mg carbon/m^3/hr on 8-21-79 as an Aphanizomenon bloom developed.

Primary productivity of the surface water in Cochiti Reservoir in 1978 and 1979 tended to be slightly greater than in 1977; however, only one measurement was in the extremely high range that occurred during the Aphanizomenon bloom in the summer of 1976 (Barton and Johnson, 1978). The highest surface productivity measured in this study, at Station 2 on August 21, 1979 was also associated with a major Aphanizomenon bloom.

The sediment load increases during spring run-off and decreases light penetration as indicated by Secchi disk visibility (Table 5). Thus in mid-May and mid-June in 1978 primary productivity decreased greatly between the surface and 1 m samples and was generally very low or not detectable at depths of 2-4 m. Light penetration increased in early July and Secchi disk values ranged from 118-265 cm in August and September. With greater light penetration primary productivity was often similar at the surface and depths of 1 and 2 m. On September 23, 1978 when Secchi disk values were about 150 cm, the highest productivity values were obtained at depths of 1 m at both stations 1 and 2 and substantial productivity was measured even at a depth of 4 m.

In 1979 the heavy run-off in late May limited Secchi disk visibility to 14 cm and significant primary productivity was measured only at the surface (actual depth about 0.5 m). Transparency increased in June and July and by July 17,1979 the photosynthetically active zone extended to 2 m. In August, as a result of the Aphanizomenon bloom, transparency greatly decreased and

the major amount of primary production occurred in the surface samples with a decline to 20-25% of the surface activity at a depth of 1 m and to nearly insignificant levels at 2-4 m.

In general, primary productivity in surface samples followed trends indicated by cell counts (Table 32). Typically, light limitations masked any effects of differences in cell numbers when productivity is compared at the surface and 2 m depth. Differences in phytoplankton community composition undoubtedly had a major effect on primary productivity. Measurement of primary productivity was a more sensitive index of the occurrence of phytoplankton than cell counts or chlorophyll a measurements (tables 32 and 35). On June 19, 1979 primary productivity was readily measured in surface samples while no phytoplankton were observed in iodine preserved samples.

The effect of two inhibitory chemicals which have been used for the control of phytoplankton blooms and aquatic macrophytes were tested in primary productivity assays at Station 1 at Cochiti Reservoir on August 17, 1979. Addition of the herbicide, Aquazine, at 0.5 ppm reduced primary productivity to 47% and 38% of control values at the surface and 1 m depth. Copper at 10 ppm reduced productivity to 54% and 47% of control values at the surface and 1 m depth. In a similar experiment conducted with surface samples at Station 2 in Abiquiu Reservoir on July 26, 1978, 0.8 ppm and 3.2 ppm Aquazine reduced primary production to 25% and 7% of the control value. The short term effects of these inhibitory chemicals may be compared to longer term effects observed during in situ experiments as discussed in section 9.

Table 39. Nitrogen fixation (acetylene reduction) activity and the concentration of cyanobacterial filaments (as nitrogen) at Station 2 in Abiquiu Reservoir.

Date	Depth m	Phytoplankton N mg/l	C_2H_2 Reduced n moles/l hr	Sp. Activity n moles/hr mg N	Secchi cm
7/26/78	Surface		53.0 ± 6.2		48
(1225-1330)*	1		37.3 ± 3.1		
	2		15.9 ± 2.1		
	3		3.16 ± 0.2		
8/4/78	Surface		9.60 ± 0.5		47
(1032-1142)	1		13.6 ± 4.0		
	2		10.6 ± 3.3		
	3		7.85 ± 1.7		
9/14/78	Surface	.192 ± .027	51.8 ± 10.1	270	45
(1200-1300)	1	.182 ± .009	42.3 ± 12.3	232	
	2	.177 ± .040	27.0 ± 18.0	153	
	3	.232 ± .010	27.9 ± 4.8	120	
7/10/79	Surface	0.158 ± .013	16.3 ± 6.1	103	109
(1105-1215)	1	0.162 ± .005	13.8 ± 2.0	85.2	
	2	0.166 ± .038	9.4 ± 1.6	56.6	
8/9/79	Surface		0 ± 0		145
(1100-1210)	1		0.64 ± .51		
	2		0.36 ± .15		

*Incubation time, MST

Nitrogen fixation (acetylene reduction) was measured at Abiquiu Reservoir on several dates when cyanobacteria were present (Table 39). Moderate rates of nitrogen fixation (53 n moles C_2H_2 reduced/liter hr) were measured in surface samples on July 26, 1978 and these declined substantially on August 4, 1978. The number of cyanobacteria and heterocysts were similar on both dates; however, primary productivity of surface samples also decreased suggesting that a decline in the physiological activity of the cells occurred during this time period. By September 14, 1978 the number of Aphanizomenon cells had increased, primary productivity (Table 37) of the surface samples was quite high, and nitrogen fixation rates were comparable to surface and 1 m rates on July 26, 1978. On July 10, 1979 nitrogen fixation rates were fairly low as was primary productivity although Aphanizomenon was abundant and most filaments included heterocysts. The very low nitrogen fixation activity on August 9, 1979 corresponds to a time when very few cyanobacteria and no heterocysts were observed in cell counts.

The determination of cyanobacteria filament nitrogen in the nitrogen fixation assays provides a replicated measure of the depth distribution of cyanobacterial filaments. On August 14, 1978 similar amounts of filaments were present at the surface, at 1 and 2 m depths and slightly more filaments were present at the 3 m depth. By comparing the specific activity of nitrogen fixation (n moles C_2H_2 reduced/hr mg nitrogen) at various depths, it is apparent that nitrogen fixation activity per mg filament nitrogen decreased only slowly with depth while primary productivity declined rapidly with depth in the summer of 1978 when light penetration was limited. This suggests that much of the energy required for nitrogen fixation is derived

from respiration rather than directly from photosynthesis. Furthermore, appreciable nitrogen fixation may have occurred at greater depths which were not sampled in this study. The lower specific activity of nitrogen fixation on September 10, 1979 provides additional evidence that the physiological activity of cyanobacterial filaments was lower on this date than on August 14, 1978.

Based on the number of electrons transferred, a conversion factor of three moles of acetylene reduced per one mole nitrogen gas (N_2) reduced to ammonium is widely used (Burris, 1974). We suggest multiplication of the hourly rate of acetylene reduction measured at mid-day by 10 to estimate the daily rate to account for expected lower rates in the afternoon and minimal rates at night. Applying these factors to the rate of actylene reduction on September 14, 1978 (51.8 n moles/1 hr), it is estimated that 4.8 micrograms of nitrogen/liter were fixed per day. This represents about 2.5% of the nitrogen present in cyanobacterial filaments or 0.8% of the total nitrogen in the surface water sample. The estimated amount of nitrogen fixed was equal to 40% of the amount of nitrate-nitrogen but only 3.7% of the amount ammonium-nitrogen which was unusually abundant in the water on this date (computed from data in tables 14, 15, and 16.)

Nitrogen fixation rates (as acetylene reduction) for Cochiti Reservoir are tabulated in Table 40. In 1978 nitrogen fixation rates increased from negligible rates on 8-10-78 to relatively high rates of 103-215 n moles of acetylene reduced/liter hr on 9-07-78 as the abundance of both Aphanizomenon and Anabaena increased (Table 32).

Based on the distribution of filament nitrogen, cyanobacteria were uniformly located throughout the water column from surface to 3 m on August

Table 40. Nitrogen fixation (acetylene reduction) activity and the concentration of cyanobacterial filaments (as nitrogen) at Station 1 in Cochiti Reservoir.

Date	Depth m	Phytoplankton N mg/1	C_2H_2 Reduced n moles/1 hr	Sp. Activity n moles/hr mg N	Secchi cm
8/10/78	Surface	0.096	trace		
(1050-1150)*	1	0.119 ± .013	trace		141
	2	0.102 ± .042	trace		
	3	0.115 ± .026	trace		
8/17/78	Surface		2.68 ± .92		265
(1035-1150)	1		1.27 ± .12		
	2		1.93 ± .30		
9/7/78	Surface	0.138 ± .011	215 ± 28	1558	200
(0935-1050)	1	0.121 ± .011	185 ± 53	1529	
	2	0.080 ± .006	103 ± 10	1288	
	3	0.097 ± .011	180 ± 13	1856	
9/28/78	Surface	0.105 ± .021	54.2 ± 1.8	516	157
	1	0.108 ± .015	39.4 ± 20.7	365	
	2	0.143 ± .013	63.5 ± 6.6	444	
	3	0.113 ± .003	62.5 ± 5.5	553	
	4	0.129 ± .035	56.6 ± 2.6	439	
8/21/79	Surface	0.139 ± .023	11.4 ± 2.3	82.2	36
(1000-1115)	1	0.103 ± .018	5.2 ± 0.5	50.3	
	2	0.080 ± .004	1.15 ± 0.82	14.4	
	3	0.074 ± .002	0.58 ± 0.54	7.8	
	4	0.066 ± .011	1.54 ± 0.54	23.3	

*Incubation time, MST.

10, 1978 while on September 7, 1978 slightly more filaments were present at the surface and 1 m depth than at the 2 and 3 m depths. Specific activity of nitrogen fixation was quite high on September 7, 1978 and was essentially constant from the surface to a depth of 3 m. While light penetration was quite deep (Secchi disk value of 200 cm), primary productivity decreased regularly with depth and the productivity at 3 m was only 25% of the surface rate. Thus rates of nitrogen fixation were quite high at depths where photosynthesis was severely light limited.

The estimated amount of nitrogen fixed per day using the surface value for acetylene reduction on September 7, 1978 is 20 µg nitrogen/liter day. This corresponds to 14.5% of the filament nitrogen, 4.3% of the total nitrogen, 200% of the ammonium-nitrogen and 250% of the nitrate-nitrogen present in the surface water at this time (computed from tables 17, 18, and 19). Thus nitrogen fixation probably was a significant factor in the proliferation of this bloom.

Relatively low levels of nitrogen fixation were measured in Cochiti Reservoir on August 21, 1979 when populations of Aphanizomenon were low at Station 1 (Table 32). Filament nitrogen, nitrogen fixation activity, and specific activity of nitrogen fixation all decreased with depth although not so sharply as primary productivity (Table 38). Higher rates of nitrogen fixation were measured on September 7, 1979 and are discussed in relation to diurnal variations in nitrogen fixation in a subsequent section.

Laboratory bioassay to determine limiting nutrients

The growth yield of A. flos-aquae in the autoclaved reservoir water was generally greater than the growth of S. capricornutum (Table 41). The reason for the low growth values with both phytoplankton on August 21, 1979

in Cochiti Reservoir water is not understood but would suggest that compounds inhibitory for cyanobacterial and algal growth occurred in the reservoir water or were produced as a result of the autoclave-heat treatment.

Growth responses of A. flos-aquae and S. capricornutum in the reservoir water with various nutrient supplements are shown in tables 42 and 43. Inoculation of these algae into the reservoir water without nutrient supplements resulted in little growth. Multiple nutrient limitation of growth was suggested with highest growth values resulting from additions of nitrogen, phosphorus and iron - EDTA. The low values of growth in the water supplemented with nitrogen, phosphorus, iron and micronutrients as compared to the reservoir water supplemented with the AAP medium indicates that carbon limitation often occurred in the laboratory bioassay system. Perhaps the pH of the autoclaved water is too low thereby decreasing the solubility of carbon dioxide. This pH effect could be avoided in the future by adjusting the pH with a non metabolized buffer such as Tris (hydroxymethyl) aminomethane. The problem of carbon dioxide availability in the algal bioassay procedure observed in this study supports the previous investigation by Murray et al. (1971).

The limiting nutrients for growth of phytoplankton are summarized in Table 44. Growth responses of S. capricornutum (Table 42) and of A. flos-aquae (Table 43) for the additives were fairly comparable and although A. flos-aquae can fix dinitrogen, nitrate supplements occasionally stimulated growth. Iron was a limiting factor of growth in both reservoirs. The stimulation of growth through EDTA additions could indicate that EDTA holds the Fe^{3+} in solution or that cations toxic to the phytoplankton were

Table 41. Growth of phytoplankton in reservoir water after addition of nutrients in AAP medium.

		Cell mass (mg dry wt/10 ml)	
Abuquiu Reservoir	Date	*Anabaena flos-aquae*	*Selenastrum capricornutum*
	5/30/78	0.863(0.214)[1]	1.137(0.048)
	7/19/78	2.253(1.888)	1.160(0.339)
	8/04/78	0.710(0.042)	1.142(0.122)
	11/21/78	1.075(0.240)	1.082(0.100)
	4/18/79	0.843(0.138)	0.965(0.001)
Cochiti Reservoir	3/09/78	0.714(0.227)	0.816(0.037)
	5/16/78	1.217(0.696)	1.023(0.241)
	7/06/78	1.558(0.304)	-
	8/10/78	0.483(0.067)	-
	8/29/78	1.133(0.053)	0.945(0.154)
	10/28/78	1.304(0.273)	-
	4/05/79	1.540(0.750)	1.230(0.380)
	8/21/79	0.742(0.085)	0.540(0.180)

[1]Values in ( ) are standard deviations.

Table 42. Bioassay of nutrient availability in reservoir water using Selenastrum capricornutum. Growth response for each addition is expressed as a percent of growth in AAP medium[1].

Date	None	N	P	N+P	N+P+ Fe	N+P+Fe +Micro	Fe	Micro	EDTA
Abiquiu Reservoir									
5/30/78	2	6	5	20	36	13	11	0	8
7/19/78	39	18	48	23	116	102	19	17	43
8/04/78	16	93	53	111	135	129	140	59	75
11/21/78	16	30	13	37	41	8	7	3	
4/18/79	24	26	8	30	30	13	8	8	8
Cochiti Reservoir									
3/09/78	32	19	22	65	88	68	20	8	28
5/16/78	0	10	5	19	55	37	7	16	5
7/06/78	-	-	-	-	-	-	-	-	-
8/10/78	-	-	-	-	-	-	-	-	-
8/29/78	5	15	8	32	39	37	7	11	10
10/28/78	-	-	-	-	-	-	-	-	-
4/05/79	33	45	28	33	51	41	105	11	68
8/21/79	3	47	14	70	54	51	23	15	8

[1]Values are calculated as:

$$\frac{\text{growth in reservoir water + nutrient specified}}{\text{growth in reservoir water + AAP medium nutrients}} \times 100 = \%$$

N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ + EDTA
Micro = Micronutrients in AAP medium
EDTA = Ethylene diaminetetraacetic acid

Table 43. Bioassay of nutrient availability in reservoir water using Anabaena flos-aquae
Growth response for each addition is expressed as a percent of growth in AAP medium[1].

Abiquiu Reservoir

Date	None	N	P	N+P	N+P+ Fe	N+P+Fe +Micro	Fe	Micro	EDTA
5/30/78	18	23	51	39	62	43	28	38	21
7/19/78	32	35	46	48	66	93	93	-	43
8/04/78	31	94	32	88	76	30	30	36	21
11/21/78	46	50	28	62	85	57	57	9	40
4/18/79	10	29	30	29	38	22	22	25	22

Cochiti Reservoir

3/09/78	29	41	39	56	88	65	56	34	32
5/16/78	15	15	24	18	44	38	20	19	17
7/16/78	69	60	65	17	118	58	107	57	97
8/10/78	27	27	57	27	65	63	24	29	40
8/29/78	4	7	18	12	49	21	18	14	9
10/28/78	6	6	12	21	34	25	9	4	4
4/05/79	16	124	128	100	139	73	116	19	64
8/21/79	5	1	15	11	147	145	7	97	111

[1]Values are calculated as:

$$\frac{\text{growth in reservoir water + nutrient specified}}{\text{growth in reservoir water + AAP medium nutrients}} \times 100 = \%$$

N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ + EDTA
Micro = micronutrients in AAP medium
EDTA = Ethylene diaminetetraacetic Acid

Table 44. Limiting nutrient for growth of phytoplankton as determined by bioassay methods.

Date	*Selenastrum capricornutum*					*Anabaena flos-aquae*				
	N	P	Fe	Micro	Chelator[2]	N	P	Fe	Micro	Chelator[2]
Abiquiu Reservoir										
5/30/78	+	+	+		+		+	+	+	
7/19/78		+	+				+	+		+
8/04/78	+	+	+	+	+	+				
11/21/78	+		+					+		
4/18/79	+	+				+	+	+		+
Cochiti Reservoir										
3/09/78	+	+	+			+		+		
5/16/78	+	+	+	+			+	+		
7/06/78								+		+
8/10/78							+	+		+
8/29/78	+	+	+				+	+	+	
10/28/78							+	+		
4/05/79	+		+		+	+	+	+		+

[1]Nutrient was determined to be limiting for growth if it stimulated growth by more than 5% over the growth in the reservoir water with no addition.

[2]Chelator activity is designated as effect of EDTA.

present in the reservoir water. The addition of EDTA (chelator) to the bioassay system has been found to be effective in assessing the problem of waters enriched with toxic heavy metals (Miller, et al., 1975). It is also likely that micronutrients could be solubilized by the EDTA from the suspended particles in the reservoir water. Certainly this EDTA stimulation is interesting but unexplained at this time.

In situ evaluation of chemical additives

The reservoir water was evaluated at four different sampling times, by the cubitainer method to determine limiting nutrients for phytoplankton and to determine the effectiveness of chemicals in controling phytoplankton blooms. Three test periods were at Cochiti Reservoir, at times when the phytoplankton were not very abundant, and one test was conducted at Abiquiu Reservoir at a time when an Aphanizomenon bloom was occurring.

The in situ bioassay indicated that iron was a limiting nutrient for growth. A substantial increase in phytoplankton density was observed in Cochiti Reservoir following the addition of phosphorus plus Fe^{3+} as the EDTA chelate (tables 45, 46 and 47). Because Cochiti Reservoir was both phosphorus and iron limited for cyanobacterial growth, the effect of iron addition was not observed unless phosphorus was added with iron. The measurement of chlorophyll-a was supportive of these cell measurements (Table 48). At Abiquiu Reservoir (Table 49), the addition of iron was the only single nutrient which stimulated growth. At Abiquiu Reservoir as at Cochiti Reservoir, the greatest cell increase followed the addition of phosphorus and iron.

The form of Fe^{3+} added to water from Cochiti Reservoir did not appear to affect the cell growth. Iron chelated with EDTA or EDDHA or unchelated iron

Table 45. Field studies on chemicals added to Cochiti Reservoir.

Variable Examined	Addition to reservoir water[1]							
Phytoplankton	None[2]	P	P+Fe	Fe	N+P+Fe	N+P+Fe+Cu	N+P+Fe Aquazine	Aquazine
Aphanizomenon				362(0)[3]	21,300(4.2)		7,148(0)	
Schroederia			2,557					
Ankyra			852	500		10,052		
Closterium			1,705					
Ankistrodesmus	1,750		6,820		72,900		1,456	
Scenedesmus					1,800			
Navicula	625							
Diatoma	625				9,900		250	1,212
Tetrallantos						3,130		
Gleocystis	312	757						
Selenastrum					1,800	1,290		
Denticula		474		376	7,200			
Pediastrum					900			
Microcystis		726			1,800			
Chlorococcum						391		
Total cells/ml	3,312	1,957	11,934	1,238	117,600	14,863	8,854	2,817

[1]Experiment was initiated on 8/10/78 and terminated on 8/17/78.

N = $NaNO_3$

P = KH_2PO_4

Fe = $FeCl_3$ + EDTA

Micro = micronutrients in AAP medium

EDTA = Ethylene diaminetetraacetic Acid

[2]At the initiation of the experiment the water in cells per ml: Diatoma, 2,952 and Aphanizomenon, 2,624 with no heterocysts present.

[3]Values in parentheses refer to heterocyst abundance with expression as $\frac{\text{heterocysts}}{\text{total cells}} \times 100 =$ %.

Table 46. Field Bioassay of nutrient availability in Cochiti Reservoir.

Measurement	Addition to Water[1]							
	None	N	P	Fe	N + P	N + P + Fe	Fe(EDDHA)	$FeCl_3$
Phytoplankton								
Microcystis		805		945				
Anabeana			1,650(0)[2]					
Diatoma				1,417				
Ankistrodesmus	665				1,920	8,055		
Crucigenia					640	5,370	545	
Closterium					640			
Denticula					640			
Tetrallantos						7,160		
Aphanizomenon						28,640(6.2)	300	
Meridon						895		
Gloeocystis								349
Total Cells/ml	665	805	1,650	2,362	3,840	50,120	845	349
pH	7.2	7.35	7.1	7.55	8.1	8.2	7.3	7.25

[1]Experiment was started on 8/21/78 and terminated on 8/29/78.

Abbreviations are as follows:
N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ + EDTA
$FeCl_3$ = $FeCl_3$ was added without a chelator
Fe(EDDHA) = sodium ferric ethylene diamine di - (0-hydroxy phenylacetate)

2Values in parenthesis are percent of cells as heterocysts.

Table 47. Effect of nutrient additions on phytoplankton activity in Cochiti Reservoir.

Measurement	Addition to Water[1]								
Phytoplankton	None	N	P	Fe	N+P	N+P+Fe	P+Fe	Fe(EDDHA)	$FeCl_3$
Diatoma	860								
Aphanizomenon		2388(0)[2]	1365						
Gloeocystis		5684	2292	2779	1666	7435	13090		
Ankistrodesus			2550		1409	785			
Denticula			460		246	1060	1942		
Schroederia	887		277	881	5138	3972			96
Tetrallantos	2690				417	262			493
Hantzchia							500		
Total cells/ml	4437	8072	6944	4655	8876	13776	15532	0	3931
pH	8.65	9.1	8.7	8.9	9.1	9.7	9.05	8.7	8.0

[1]Experiment was started on 9/28/78 and terminated on 10/06/78.

Abbreviations are as follows:
N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ was added without a chelator
Fe(EDDGA) = sodium ferric ethylene diamine di - (0-hydroxy phenylacetate)

[2]Value in parenthesis is percent of cells as heterocysts.

Table 48. Chlorophyll-a concentrations in contained water at Cochiti Reservoir one week after addition of chemicals.

A. Chemicals for field bioassay[1]

Addition	Chlorophyll (µg/ℓ)
None	3.7
N	0.9
P	2.5
Fe (EDDHA)	1.8 (0.2)[2]
$FeCl_3$	1.7 (0.1)
N + P + Fe	17.2

B. Chemicals for control of phytoplankton bloom

Adddition	Chlorophyll (µg/ℓ)
None	3.7
Cu	2.6
Cu + Fe	2.4
Cu + Fe (EDDHA)	1.1 (0.7)
Cu + P + N + Fe	27.7
Aquazine	2.3
Aquazine + P + N + Fe	2.0

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[1]Experiment was initiated on 8/21/78 and terminated on 8/29/78.
Abbreviations are as follows:
N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ was added without a chelator
Fe(EDDHA) = sodium ferric ethylene diamine di - (0-hydroxy phenylacetate)

[2]Values in ( ) are phaeophytin which are indicated as being measurable only at these times.

Table 49. Field bioassay of nutrient availability in Abuqiui Reservoir.

Addition	pH	Phytoplankton (cells/ml)					
		Aphanizomenon	Anabaena	Diatoma	Ankistrodesmus	Gloeocystis	Total
None	9.7	181,775(2.6)[2]	26,200(11.8)			2,400	210,375
N	9.6	93,827(6.6)	27,700(5.0)				121,527
P	9.3	105,922(3.4)	35,788(10)		617		142,327
Fe	8.9	224,330(1.8)	32,512(9.6)			1.735	258,577
N + P	9.5	98,168(3.8)	6,267(0)	1,950	17,550	4,875	128,810
P + Fe	9.5	254,287(3.4)	51,825(9.5)			2,147	308,259
N + P + Fe	10.1	59,900(3.6)	7,875(11.1)		8,510		76,285

[1]Experiment was initiated on 7/19/78 and terminated on 7/26/78.

Abbreviations are as follows:

N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ + EDTA

[2]Values in parenthesis are percent of cells as heterocysts.

gave about the same growth response. EDTA chelated iron gave slightly higher cell densities which may be due to the EDTA solubilizing other metals in the water. In future studies it would be important to test for EDTA stimulation of growth using this in situ method.

Nitrogen is shown to be a limiting nutrient for algal growth in Cochiti Reservoir. Since the dominant forms of phytoplankton in Abiquiu Reservoir were cyanobacteria, the addition of nitrogen had little effect on growth of phytoplankton.

The variety of phytoplankton observed in the cubitainers at Cochiti Reservoir was greater than that observed in routine phytoplankton enumeration studies. The large sampling used in this test no doubt results in selecting phytoplankton of low numbers. Although many genera of algae are present, the low nitrogen of the water prevents great levels of algal growth.

One advantage of this in situ cubitainer method is that chemicals can be added to portions of the reservoir water without affecting the entire water body. We examined three chemicals as controls of phytoplankton: Cu^{2+}, Aquazine and methyl viologen (paraquat). All three chemicals reduced phytoplankton in Cochiti Reservoir when added singularly (Tables 45, 50 and 51). The best evidence for effective control of phytoplankton was obtained when the chemicals were added along with nitrogen, phosphorus, and iron. In separate experiments, Aquazine inhibited growth by 92% (Table 45), 99% (Table 50) and 37% (Table 51). Not all phytoplankton species are equally sensitive to Aquazine. In the study at Abiquiu Reservoir (Table 52), growth of Aphanizomenon was inhibited 85% while that of Anabaena was completely inhibited.

Table 50. Effect of chemical additions on phytoplankton activity in Cochiti Reservoir.

Measurements	Addition to water [1]							
	None	Cu	Aquazine	N + P + Fe + Cu	Fe + Cu	Fe(EDDHA) + Cu	N + P + Fe + Cu	N + P + Fe + Aquazine
Diatoma		795				160		549
Ankistrodesmus	665	265		9,458			6,768	
Denticula			555			250		
Pediatrum				356			1,301	
Tetrallantos				1,425			5,205	
Crucigenia				712			10,162	
Gloeocystis					1,190	2,120		
Anabaena					595(0)[2]			
Staurastrum						165		
Aphanizomenon							2,362(0)	
Total cells/ml	665	1,060	555	11,951	1,785	2,695	25,799	549
pH	7.2	7.15	7.2	7.95	7.1	7.1	7.9	7.15

[1]Experiment was started on 8/29/78 and terminated on 9/07/78.

Abbreviations are as follows:
N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ was added without a chelator
Fe(EDDGA) = sodium ferric ethylene diamine di - (0-hydroxy phenylacetate)

[2]Values in parenthesis are percent of cells as heterocysts.

Table 51. Effect of copper, Aquazine, and methyl viologen on phytoplankton activity in Cochiti Reservoir.

Measurement	Addition to Water[1]									
	None	Cu	Aquazine	N+P+Fe+Cu	N+P+Fe+ Aquizine	Fe+Cu	Fe(EDDHA) + Cu	$FeCl_3$+Cu	N+P+Fe+MV	MV
Phytoplankton										
Ceratium				375						
Schroederia	887	1662	502	4429		1497		785		
Tetrallantos	2690									
Diatoma	860			1850		276				
Meridian		2931								
Ankistrodesmus		1624		2220						
Gloeocystis			687	379	8625		987			
Dentricula			251	1106						
Crucigenia				369				5120		
Staurastrum				375						
Total cells/ml	4437	6217	1440	11130	8625	1773	987	5905	0	0
pH	8.65	8.2	8.25	9.2	9.5	8.5	8.2	8.05	8.55	8.5

1. Experiment was started on 9/28/78 and terminated on 10/06/78.
   Abbreviations are as follows:
   N = $NaNO_3$
   P = KH_2PO_4
   Fe = $FeCl_3$ was added without a chelator
   Fe(EDDGA) = sodium ferric ethylene diamine di - (0-hydroxy phenylacetate)
   MV = methyl viologen

Table 52. Effect of copper and aquazine on phytoplankton activity in Abiquiu Reservoir.

Addition To Water[1]	pH	Phytoplankton (cells/ml)						
		Aphanizomenon	Anabaena	Diatoma	Gloeocystis	Ankistrodesmus	Microcystis	Total
None	9.7	181,775(2.6)[2]	26,200(11.8)		2,400			210,375
Cu	8.1	4,823(0)	28,840(14.6)					33,663
Aquazine	7.8	29,267(1.6)	0		1,673			30,940
N+P+Fe+Cu	9.5	1,866(0)	30,808(14.6)	549	33,825	8,126	9.641	84,815
N+P+Fe+ Aquazine	9.6	28,500(0)	0	5,700	15,200	6,650		56,050

[1]Experiment was initiated on 7/19/78 and terminated on 7/26/78.

Abbreviations are as follows:

N = $NaNO_3$
P = KH_2PO_4
Fe = $FeCl_3$ + EDTA
Cu = $CuSO_4$

[2]Values in parenthesis are percent of cells as heterocysts.

Copper inhibited phytoplankton growth by 87% (Table 45), 76% and 49% (Table 50), and 20% (Table 51). The chlorophyll a analysis of the contained water samples did not show the copper inhibition (Table 48) because, among the phytoplankton, copper is most inhibitory to cyanobacteria. During the cyanobacteria bloom at Abiquiu Reservoir (Table 52), copper addition did not inhibit the growth of Anabaena but inhibited the growth of Aphanizomenon by 97%.

Methyl viologen was the most effective of the three inhibitors tested. Complete inhibition of algal growth was observed (Table 51). In the future it would be important to test the inhibitory effect of methyl viologen on cyanobacteria. Certainly methyl viologen has the potential of being an excellent phytoplankton inhibitor and it has not been previously employed (Leischman, et al., 1979; Janik et al., 1980).

Diurnal distribution of cyanobacteria

A study was conducted on September 7, 1979 to assess the daily variation in the distribution of cyanobacterial filaments and nitrogen fixation activity during an Aphanizomenon bloom at Station 2 in Cochiti Reservoir. The distribution of cyanobacteria was evaluated by counts of filaments, cells, and heterocysts (Figure 9 and Table 53), filament nitrogen concentrations (Table 54 and Figure 10), and chlorophyll a concentrations (Table 54 and Figure 11). The results of cell counts when phytoplankton were concentrated by either the iodine settling method (Lugols preserved) or by sieving through miracloth (FAA preserved) were obtained from single samples and are given in Table 53. Results with both methods of sample collection indicate that Aphanizomenon was by far the dominant phytoplankton, accounting for 97.5% of the cells in all samples counted while Anabaena comprised the

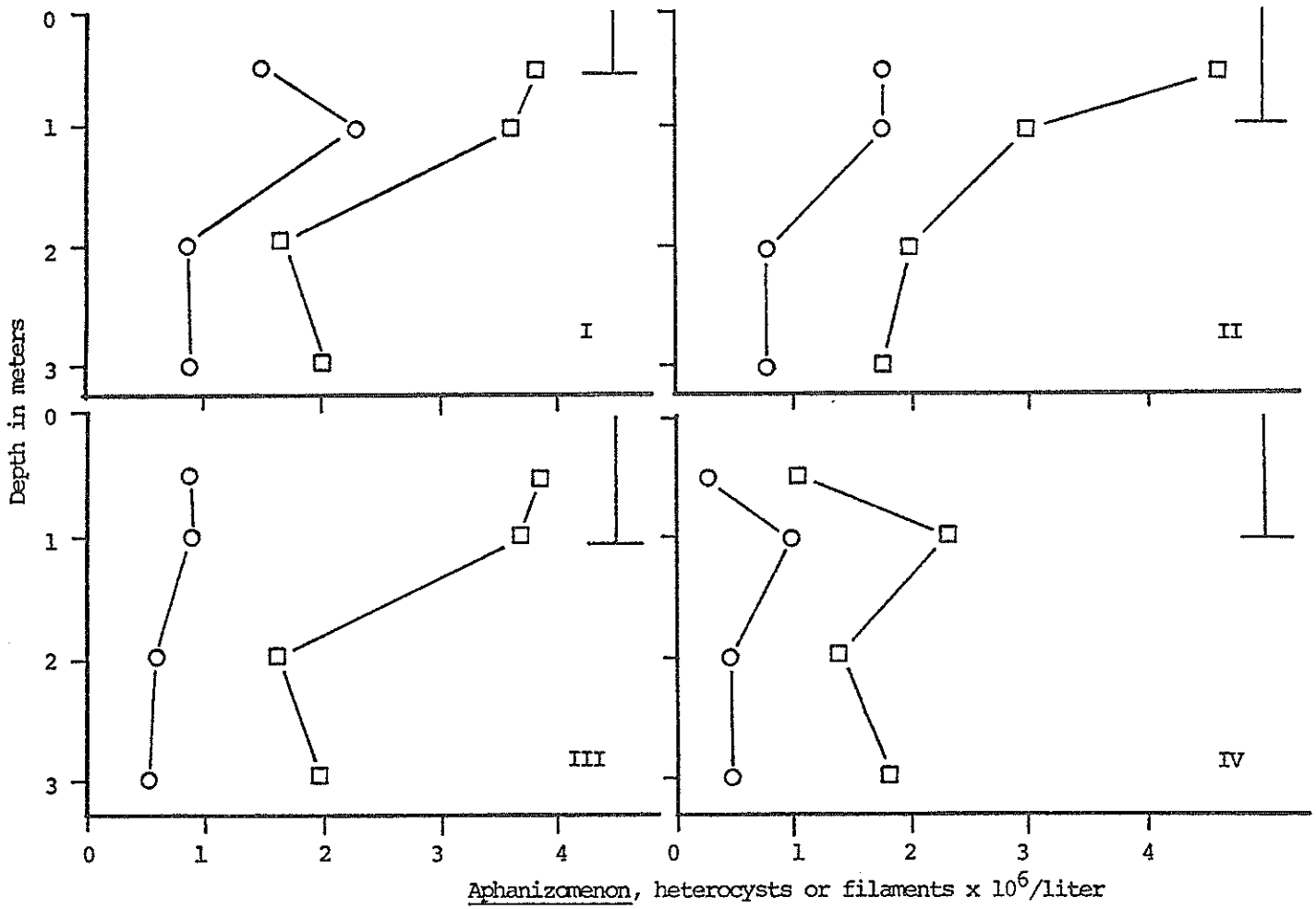

Figure 9. Distribution of heterocysts and filaments of Aphanizomenon in Cochiti Reservoir. Heterocysts, circles; filaments, squares. Time is: I, 0700; II, 1100; III, 1400; IV, 1800 MST. The Secchi disk reading is indicated by ⊥.

Table 53. Diurnal variation in the distribution of phytoplankton genera as measured by two methods at Cochiti Reservoir, Station 2 on 9-7-79.

Time* MST	Depth m	Genera	Lugols Preserved		FAA Preserved	
			heterocysts/ml	cells/ml	heterocysts/ml	cells/ml
0659	Surface	Aphanizomenon	426	73,425	1,800	62,100
		Anabaena	0	0	400	3,600
	1	Aphanizomenon	1,067	103,999	1,600	92,800
		Anabaena	0	80	600	6,600
	2	Aphanizomenon	1,176	179,215	1,000	31,600
		Anabaena	0	0	0	600
	3	Aphanizomenon	392	84,699	800	25,800
1108	Surface	Aphanizomenon	nd**	nd	2,800	83,000
	1	Aphanizomenon	nd	nd	2,800	58,800
	2	Aphanizomenon	nd	nd	600	17,000
	3	Aphanizomenon	nd	nd	1,000	25,200
		Anabaena	nd	nd	0	6,000
1422	Surface	Aphanizomenon	488	61,951	1,200	32,400
	1	Aphanizomenon	1,887	33,962	600	27,600
		Anabaena	0	784	0	1,600
	2	Aphanizomenon	784	95,687	400	26,400
		Anabaena	0	0	0	4,000
	3	Aphanizomenon	930	36,744	400	26,000
1802	Surface	Aphanizomenon	0	30,769	200	11,800
	1	Aphanizomenon	784	54,901	1,600	48,400
		Anabaena	0	13,328	0	0
	2	Aphanizomenon	0	49,432	200	13,600
	3	Aphanizomenon	0	26,139	800	33,200

*The time refers to the initiation of acetylene reduction measurements; phytoplankton samples were collected about 30 minutes prior to this time.

**Not determined.

Table 54. Diurnal variation in phytoplankton distribution and nitrogen fixation (acetylene reduction) activity in Cochiti Reservoir at Stateion 2 on 9-7-79.

Time MST	Depth m	Phytoplankton N* mg/l	C_2H_2 Reduced** n moles/l hr	Sp. Activity n moles/hr mg N	Chlorophyll µg/l	Phaeophytin µg/l
0659-0800	Surface	.456 ± .024	47.6 ± 6.1	104.3	29.8	nd††
	1	.398 ± .053**	47.6 ± 6.2	119.6	16.8	nd
	2	.401 ± .018	33.5 ± 5.5	83.5	23.3	nd
	3	.230 ± .015	22.8 ± 0.3	99.2	13.1	nd
1108-1208	Surface	.349 ± .058**	139.8 ± 11.2	400.6	17.2	nd
	1	.402 ± .059	121.0 ± 32.2	301.0	24.0	nd
	2	.316†	64.0 ± 0.5	202.4	23.6	nd
	3	.152 ± .019	21.8 ± 2.4	143.7	9.3	nd
1422-1522	Surface	.238 ± .050**	44.5 ± 11.4	187.0	19.2	nd
	1	.266 ± .026	67.4 ± 6.8	253.5	9.6	nd
	2	.222 ± .022	40.9 ± 8.0	184.3	10.4	nd
	3	.254 ± .032	37.3 ± 6.6	146.9	8.3	160
1802-1918	Surface	.176 ± .026**	7.5 ± 0.7	42.4	5.6	nd
	1	.208 ± .009	17.0 ± 1.1	81.8	9.0	nd
	2	.203 ± .032	17.3 ± 0.4	85.2	16.7	nd
	3	.202 ± 0.21**	16.6 ± 3.2	82.4	3.0	6.1

*$\bar{N}$ = 3 except where otherwise indicated
**$\bar{N}$ = 2
†$\bar{N}$ = 1
††not detected

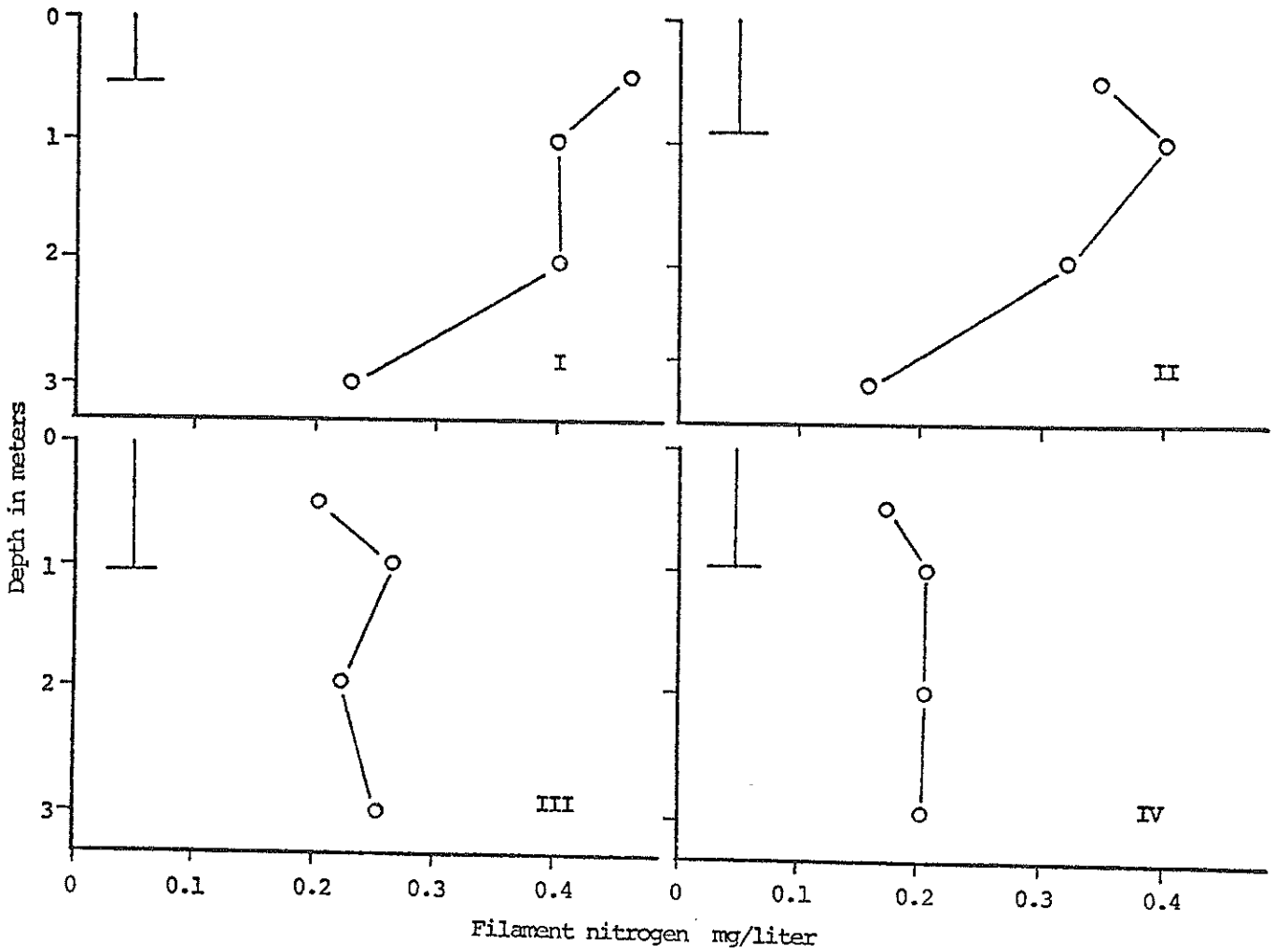

Figure 10. Aphanizomenon density in Cochiti Reservoir as determined by filament nitrogen. Time is: I, 0700; II, 1100; III, 1400; IV, 1800 MST.

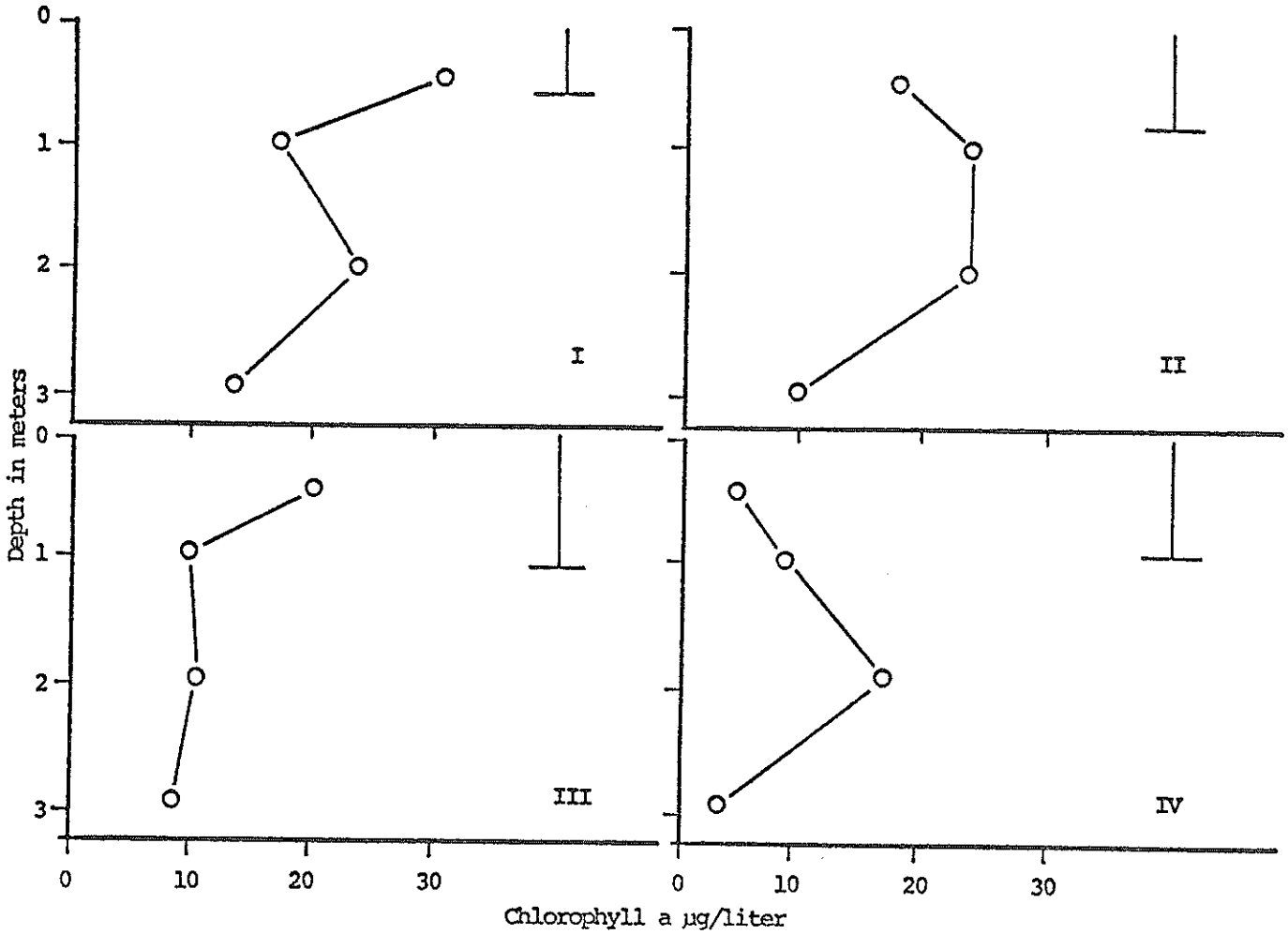

Figure 11. Diurnal distribution of phytoplankton in Cochiti Reservoir as determined by Chlorophyll-a measurements. Time is: I, 0700; II, 1100; III, 1400; IV, 1800 MST.

remaining 2.5% of the cells. The average percentage of heterocysts of total Aphanizomenon cells was 2.8% in FAA preserved samples compared to 0.95% in Lugols preserved samples. This difference in the relative number of heterocysts as well as the lower total number of Aphanizomenon cells per ml in most FAA preserved samples, suggests that FAA was more destructive to vegetative cells than was Lugols solution. The more resistant heterocysts however, were apparently relatively stable in FAA.

The chlorophyll data in Table 54 and Figure 10 were obtained by extraction of filament samples concentrated 100 X by sieving reservoir water through miracloth and then resuspending the sample in sieved reservoir water. These unreplicated samples were then frozen in the field to reduce possible errors resulting from degradation of chlorophyll prior to analysis in the laboratory.

Of the several measures of the distribution of cyanobacteria, filament nitrogen is probably the most reliable because these values, in most instances,are the means of the three replicate samples of 100 X concentrated filaments (equivalent to one liter of reservoir water) used in the acetylene reduction assays (Table 54 and Figure 10). At dawn (0700 MST or I in figures 9-12) filaments were most abundant near the surface, decreased slightly at a depth of 1 and 2 m and substantially at 3 m based on nitrogen analyses. By 1100 (II in figures) filaments had slightly decreased near the surface and at the 2 and 3 m depths. When sampled at 1400 hrs MST (III in figures), the filament concentration had decreased at the surface, at depths of 1 and 2 m and increased at a depth of 3 m suggesting that the cyanobacteria were moving downward in the water column. At dusk (1800 IV in figures), slight

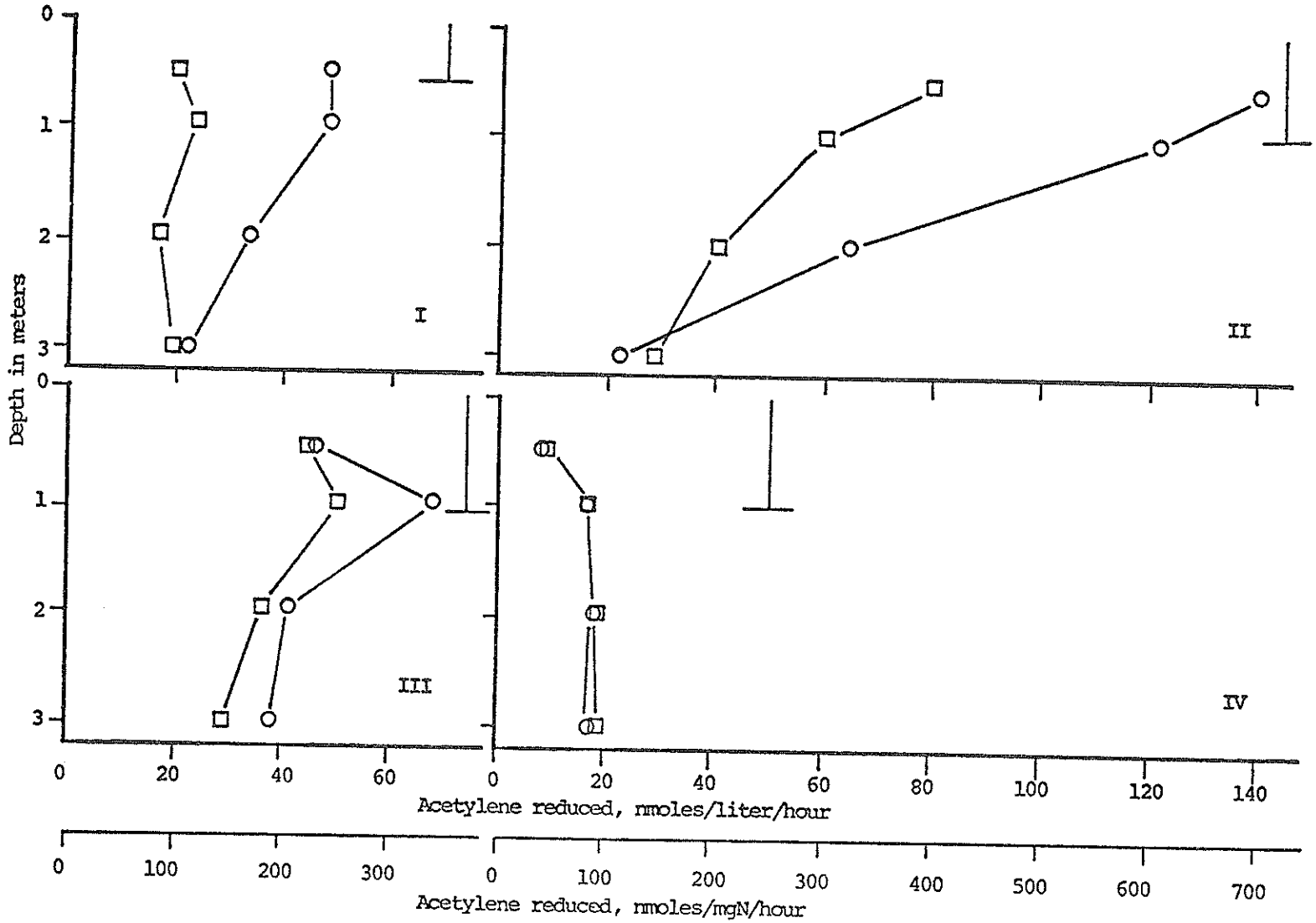

Figure 12. Diurnal nitrogen fixation in Cochiti Reservoir. Nitrogen fixed is expressed as acetylene reduced per volume of water, circles, or per mg nitrogen of cyanobacteria, squares. Time is: I, 0700; II, 1100; III, 1400; IV, 1800. MST.

decreases in filament nitrogen concentrations were noted at all depths sampled.

Similar changes in the distribution of cyanobacteria are suggested by chlorophyll a measurements (Table 54 and Figure 11). The low concentration of chlorophyll a at the 3 m depth at 1800 MST (IV in Figure 11) corresponds to a substantial amount of pheophytin suggesting that much of the cyanobacteria was moribund in this sample.

On a volume of water basis the rate of nitrogen fixation at the surface, and at 1 and 2 m depths increased from just after dawn (I) to maximum values at 1100 (II) and then progressively declined at 1400 (III) and 1800 (IV) (Table 54 and Figure 12). The rate of nitrogen fixation was lowest at a depth of 3 m at dawn and midday; however, it was comparable to most of the samples nearer the surface in the afternoon (III) and at dusk (IV).

When specific activities of nitrogen fixation are compared, it is apparent that fixation/mg filament nitrogen was nearly uniform at all depths in the early morning (I). At midday (II), maximum specific activities were measured at surface, 1 and 2 m depths. Specific activity decreased with depth corresponding to the expected decrease in photosynthetic activity with depth as a result of limited light penetration. In midafternoon (III), specific activity decreased near the surface and at 1 m. Clouds and reduced light intensity may have been responsible at least in part for decreased fixation in midafternoon. At dusk (IV), the specific activity curve coincides with the volume curve and the specific activities were similar to those observed at dawn (I).

The rate of nitrogen fixation thus is limited by light at all depths at dawn and dusk and at subsurface depths during midday. Limited light

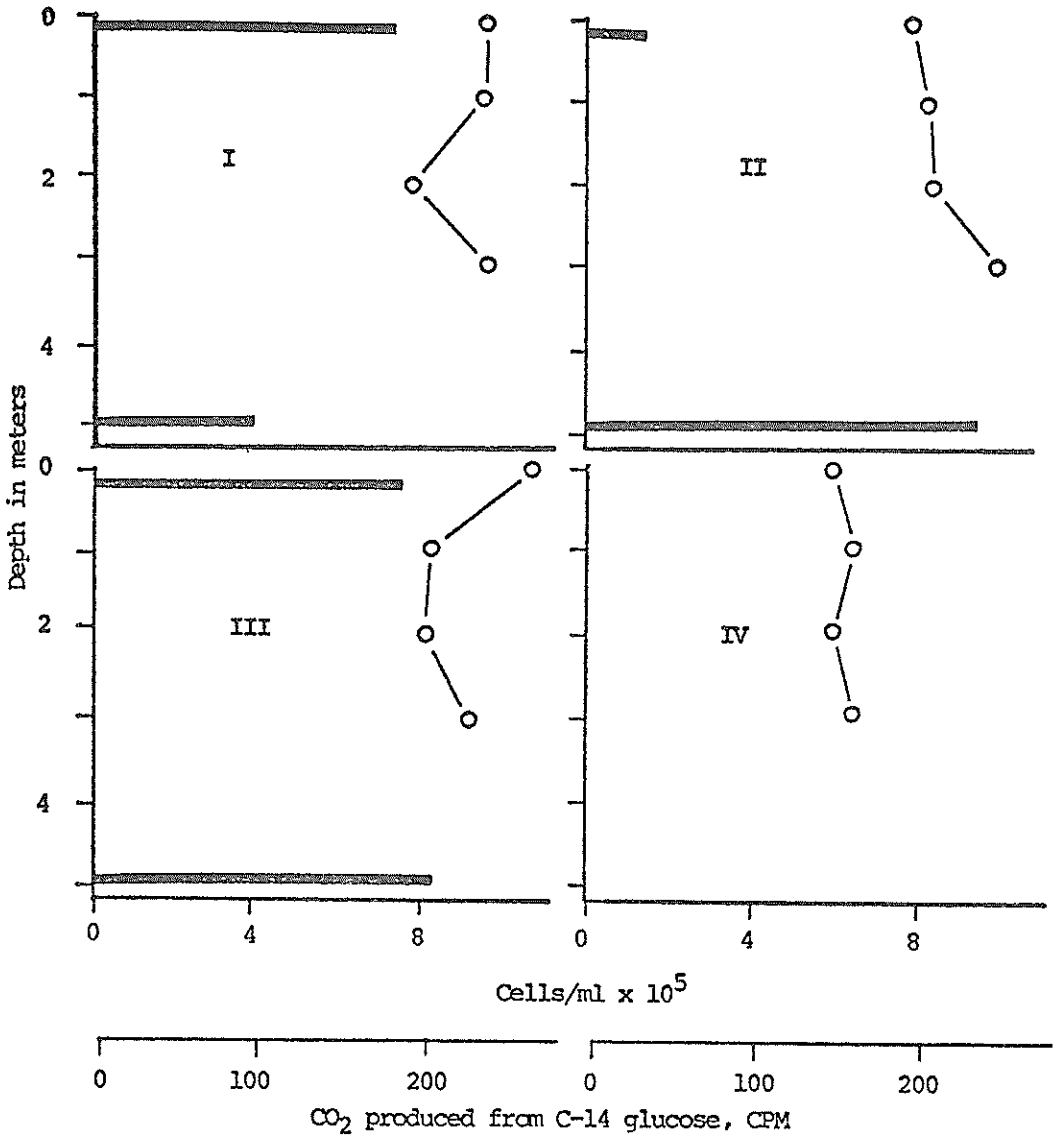

Figure 13. Diurnal distribution of bacteria in Cochiti Reservoir. Heterotrophic bacteria were measured by plate count methods, circles, and by metabolic activity, bars. Time is: I, 0700; II, 1100; III, 1400; IV, 1800 MST.

penetration is indicated by Secchi disk values of 0.5 to 1 m. The specific activity at a depth of 3 m increased only slightly during midday (II, III), and dawn or dusk activities at 3 m may be used to approximate the specific activity of nitrogen fixation in the dark. Thus we estimate that the rate of nitrogen fixation in the dark is 20-25% of the maximum specific activity observed in surface samples at midday (II). Based on midday (II) values, nitrogen fixation activity is strongly stimulated by increased light intensity; however, physiological factors are probably in part responsible for decreased activity in midafternoon (III). In order to accurately estimate the contribution of nitrogen fixation to an aquatic ecosystem, the diurnal pattern of nitrogen fixation at various depths must be further elucidated, taking into account effects of variation in light intensity, changes in the depth distribution of phytoplankton, and variation in fixation that may result from internal regulation of physiological processes (Paerl and Kellar, 1979). The single study reported here suggests correspondence with the pattern observed for several Wisconsin lakes with the maximum nitrogen fixation activity during the morning hours (Rusness and Burris, 1970; Vanderhoef et al. 1975; and Peterson et al. 1977). In addition to fixation during the day, our results indicate that activity in the dark is of sufficient magnitude to require its inclusion in an accurate estimation of the contribution of nitrogen fixation to the ecosystem.

The diurnal variations in the distribution of heterotrophic bacteria were measured in this study by plate counts as well as by the respiration of ^{14}C labeled glucose (Figure 13). Plate counts indicated that at dawn (I), greater numbers of bacteria were present near the surface than at 5 m;

however, by 1100 (II), the bacterial counts at the surface had greatly decreased while counts at 5 m had increased suggesting a downward movement of bacteria in the water column. By 1400 (III) the number of heterotrophic bacteria had again increased at the surface; however, little change was noted at 5 m. Respiration of glucose-^{14}C by heterotrophic bacteria was essentially constant from the surface to the 3 m depth at dawn (I), 1100 (II) and 1400 (III). A slight decrease in respiration of ^{14}C-glucose was noted at all depths at dusk (IV). Thus these results suggest that heterotrophic bacteria, as well as cyanobacteria, decreased to minimum numbers in the surface 3 m at dusk.

Dynamics of iron movement

The alkaline environment of Abiquiu and Cochiti reservoirs (see tables 11 and 12) would be expected to readily precipitate iron; however, it was found that only a fraction of the radiolabeled iron which was added to water from Cochiti Reservoir precipitated in a few minutes. As indicated in Figure 14, the production of some colloidal iron which was greater than 0.45 microns in diameter occurred immediately and did not increase substantially after 30 min. Perhaps the high level of soluble iron is attributed to the presence of an iron chelator in the water. The production of specific iron chelators by cyanobacteria has been implicated in species dominance (Murphy et al., 1976); however the production of an iron chelator by Aphanizomenon has not been reported.

A considerable amount of iron was taken up by the bacteria and by the phytoplankton (Figure 10). This uptake of iron was energy dependent as indicated by the inhibition with 1 x 10^{-4}M 2, 4 dinitrophenol. Furthermore, uptake of iron did not occur at 4°C. The iron uptake was primarly

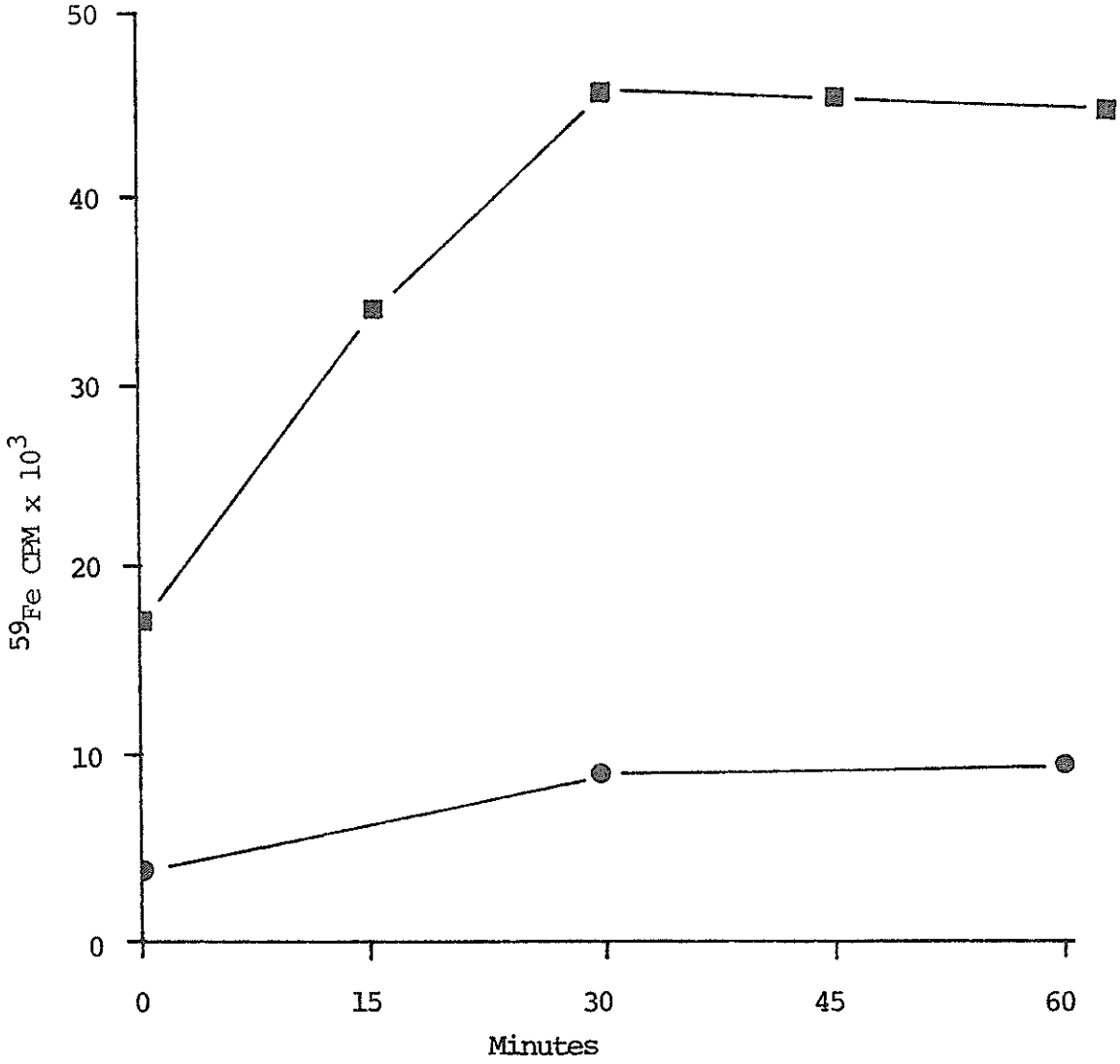

Figure 14. Formation of colloidal iron and iron uptake activity with iron added to water from Cochiti Reservoir. Colloidal iron, circles; uptake activity, squares. Experiment was conducted on 7-26-79. Water pH was 7.6 with 4 x 10^4 heterotrophic bacteria per ml and 1.2 x 10^4 Aphanizomenon per ml. 23,000 CPM of ^{59}Fe was added to each tube.

Table 55. The effect of cations on the dynamics of iron movement in alkaline water from Cochiti Reservoir

	Activity expressed as a percent of iron counted in control[1]		
Addition[2]	Colloid formation	Cellular Binding	Phytoplankton
None	100%	100%	100%
$AlCl_3$	25%	54%	31%
$CrCl_3$	343%	210%	84%
$CuSO_4$	77%	212%	21%
$La_2(SO_4)_3$	----	76%	22%
EDTA	----	11%	----

[1]Experiment was conducted with water collected on 8/08/79.

[2]Additions were at 16 ppm.

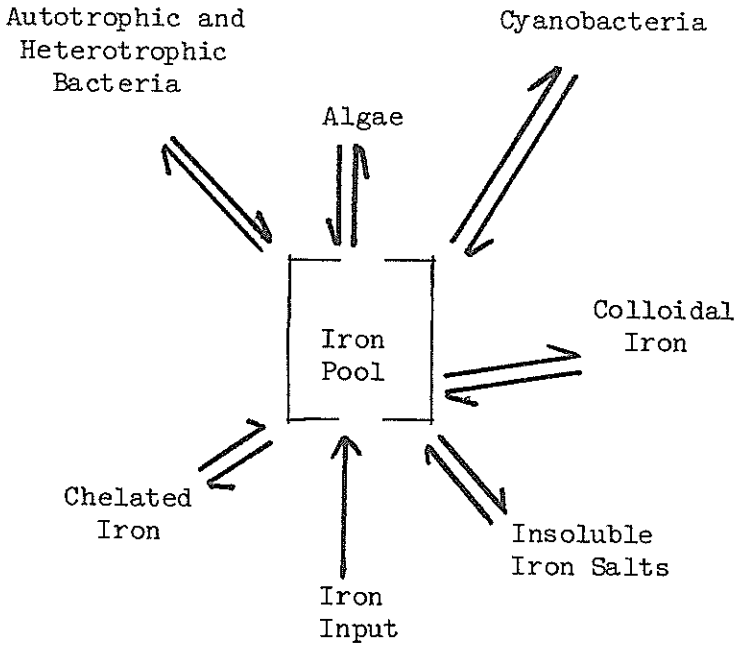

Figure 15. Dynamics of iron movement in an aquatic ecosystem.

attributed to the Aphanizomenon since about 80 percent of the radioactive iron was retained on the glass fiber filters and incubation in the dark reduced the level of iron uptake by about 75 percent. The rapid uptake of iron by the phytoplankton indicates that the cells are not saturated with iron but are in fact growing under iron limited conditions.

The three main activities of iron, which is added to reservoir water, are colloid formation, nonenergy dependent binding to cells and uptake by phytoplankton plus bacteria. The iron colloid appears to be quite large since the retention of radiolabeled iron on membranes of 0.20, 0.45 or 0.8 micron pore diameter was essentially the same. This is in contrast to the ecosystem studied by Murphy and Lean (1975) where the formation of various molecular sizes of iron was observed. Cation-iron interactions effect the formation of the iron colloid as indicated in Table 55. Ions of aluminum and copper decrease the iron colloid whereas chromium greatly increases the formation of the iron colloid. With copper there is the rapid formation of insoluble complexes which leaves a blue layer on the membrane filter. The formation of cation-iron matrices may be an important factor for iron availability in alkaline waters and should receive additional study.

Binding of iron to the cells was an immediate response which occurred at 4 C without active metabolism. Lanthanum and aluminum ions competed with iron for sites on the cells and thereby reduced the amount of iron bound. Ions of chromium and copper apparently use the cells as a nucleus for precipitation and trap iron on the cell surface thereby accounting for the increased level of cellular binding. The reduction of iron binding by EDTA indicates that the binding sites on the cells have a lower affinity for iron than does EDTA.

The transport of Fe^{3+} by phytoplankton was sensitive to ions of aluminum, chromium, copper and lanthanum (Table 10). Other microbial iron transport systems have displayed similar responses to cation inhibitions (Lankford, 1973). The high level of inhibition of iron transport by copper is of special importance since copper has been employed to control phytoplankton blooms (Elder and Horne, 1978).

As depicted in Figure 15, there are multiple exchange reactions which compete for the iron in water. When considering the overall movements of Fe^{3+} in alkaline reservoirs, it is apparent that chelated and colloidal forms of iron are very important. Chelated iron can be retained in solution by specific molecules known as ferrichromes or by other organic molecules which may be as general as humic acids. Although ferrichromes have not been demonstrated in reservoir water, it would be expected that ferrichromes are present in the water since all types of bacteria and cyanobacteria produce these iron chelatons. Colloidal iron formation is apparently influenced by cations and in waters with high concentration metal salts, the amount of colloidal iron would depend on the type of metal ion present. Generally the cyanobacteria accumulate iron at a greater rate than algae and since the cyanobacteria are generally more abundant than the other bacteria, the greatest demands for iron in these alkaline reservoirs would be by the cyanobacteria.

Humic acid in reservoir water

Water samples from Station 3 at Cochiti Reservoir and from Station 4 at Abiquiu Reservoir were collected and examined for humic acid. Of the samples tested in 1978 from collections made in March, May, June, July and August at Cochiti Reservoir, the level of humic acid was found to be from

0.01 to 0.5 ppm. Similar results were found in Abiquiu Reservoir with monthly samples taken April to September in 1979. These concentrations are much lower than that reported for river water in Florida (Martin and Pierce, 1971). Humic substances have long been considered important as chelators and solubilizers of metals in aquatic environments (Benes et al., 1976; Schnitzer and Khan, 1972). These low values for humic acids in Cochiti and Abiquiu reservoirs would indicate that iron could not be maintained in the reservoir water by the humic acids at a concentration sufficient for phytoplankton blooms. To determine the source of iron for the phytoplankton, it would be important to examine the abundance of suspended iron precipitates and iron association with the clay particles in the reservoir water.

Nutrient budgets

The total nitrogen and total phosphorus concentrations, nitrogen phosphorus ratios, and daily flow rates at the inlet (U.S. Geological Survey gauging station) and outlet of Abiquiu Reservoir are listed in tables 56 and 57. Total nitrogen and total phosphorus concentrations and average monthly flow rates for the inlet and outlet are depicted in figures 16 and 17. These concentrations were used to estimate the total nitrogen and total phosphorus flux based on the total water flow during time intervals extending to the midpoint between successive collections of water samples (Table 58 and 59). Based on these calculations, water, nitrogen, and phosphorus balances were estimated for Abiquiu Reservoir from July 25, 1978 through July 24, 1979 (Table 60).

Nitrogen concentrations entering Abiquiu Reservoir were highest in July and August, 1978 while phosphorus concentrations were highest during the

Table 56. Nitrogen and phosphorus concentrations, nitrogen phosphorus ratios, and inflow volumes at the Abiquiu inlet.

Date	Nitrogen mg/l	Phosphorus mg/l	N/P	Inflow* CFS
5-30-78	0.795 ± .035**	0.181 ± .000	4.39	1864
6-13-78	0.845 ± .276	0.068 ± .016	12.4	788
7-19-78	2.56 ± 2.36	0.183 ± .018	14.0	751
8-10-78	1.565 ± .007	0.114 ± .007	13.7	542
10-17-78	0.350 ± .014	0.038 ± .000	9.21	30
2-27-79	0.450 ± .000	0.107 ± .001	4.21	93
4-03-79	0.634 ± .047	0.276 ± .006	2.30	740
4-18-79	1.245 ± .021	0.477	2.61	2828
4-28-79	0.910 ± .028	0.268 ± .006	3.40	2346
5-15-79	0.805 ± .247	0.209 ± .011	3.85	922
6-06-79	1.065 ± .007	0.230	4.63	1725
6-19-79	0.190 ± .014	0.188 ± .001	1.01	1358
7-10-79	0.165 ± .064	0.158 ± .002	1.04	410
8-08-79	-	0.073 ± .007	-	118

* Data obtained from Albuquerque District, Corps of Engineers

** Standard deviation for duplicate samples collected in field.

Table 57. Nitrogen and phosphorus concentrations, nitrogen phosphorus ratios, and outflow volumes at the Abiquiu outlet.

Date	Nitrogen mg/l	Phosphorus mg/l	N/P	Outflow* CFS
4-04-78	0.395 ± .007**	-	-	226
5-30-78	0.570 ± .354	0.154 ± .019	3.70	1670
7-19-78	0.510 ± .085	0.239 ± .014	2.13	720
8-04-78	0.505 ± .007	0.090 ± .009	5.61	1200
10-17-78	0.680 ± .028	0.096 ± .005	7.08	26
11-21-78	0.380 ± .057	0.073 ± .000	5.21	47
2-27-79	0.480 ± .071	0.064 ± .011	7.50	142
3-16-79	1.54	-	-	624
4-03-79	0.697 ± .393	0.076 ± .000	9.17	700
4-18-79	0.520 ± .028	0.127 ± .001	4.09	1556
4-28-79	0.730 ± .141	0.110 ± .008	6.64	1411
5-15-79	0.530 ± .042	0.142 ± .004	3.73	1729
5-24-79	0.525 ± .035	0.215 ± .020	2.44	1234
6-06-79	0.740 ± .085	0.277 ± .000	2.67	1040
6-19-79	0.185 ± .064	0.270 ± .004	0.68	1009
7-10-79	0.160 ± .085	0.119 ± .010	1.34	1124
8-08-79	-	0.140 ± .030	-	94

* Data obtained from Albuquerque District, Corps of Engineers.

** Standard deviation for duplicate samples collected in field.

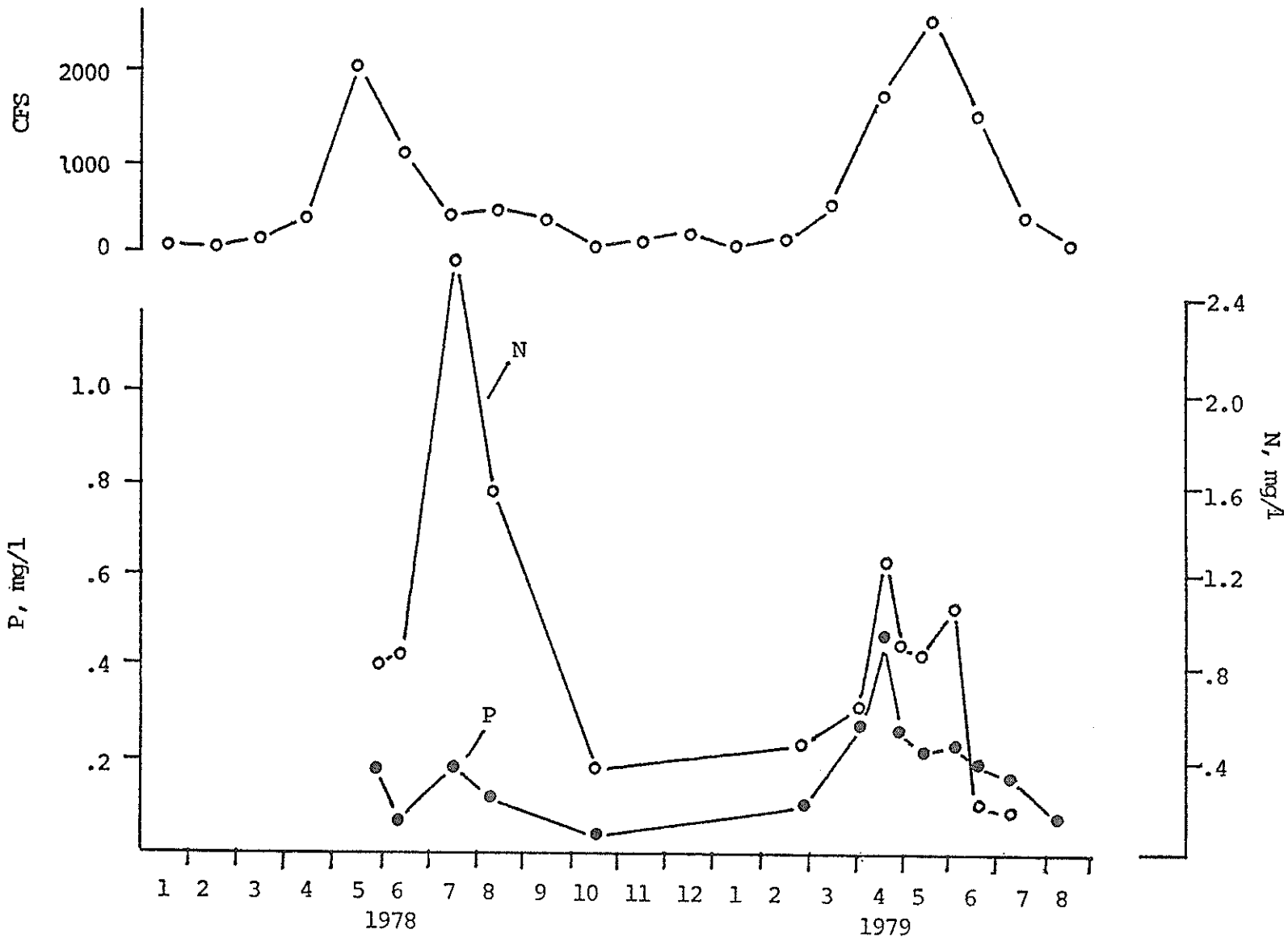

Figure 16. Total nitrogen and total phosphorus concentrations and mean monthly flow at the inlet of Abiquiu Reservoir. CFS is cubic feet per second.

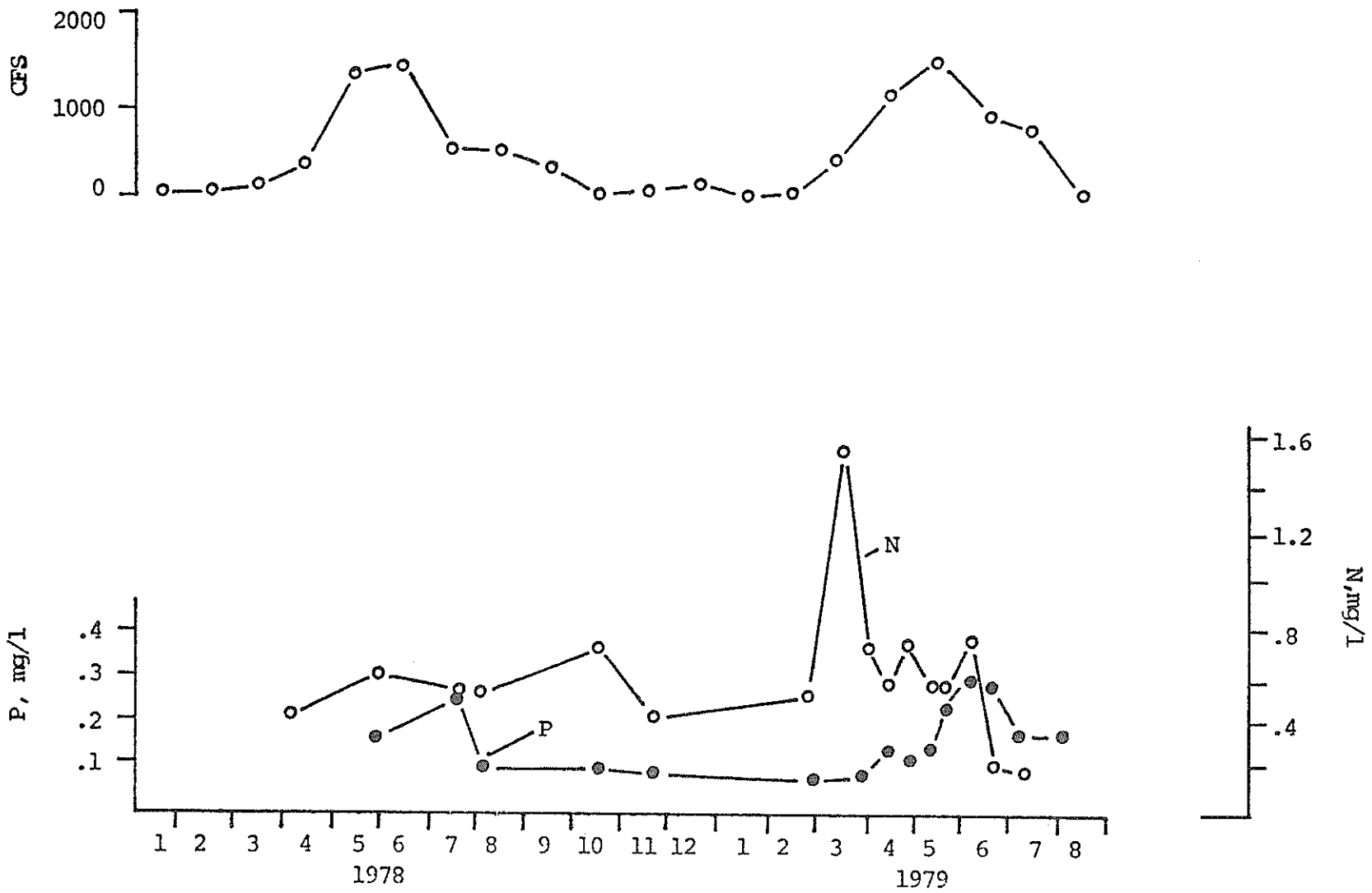

Figure 17. Total nitrogen and total phosphorus concentrations and mean monthly flow at the outlet of Abiquiu Reservoir. CFS is cubic feet per second.

Table 58. Inflow volumes and total nitrogen and total phosphorus entering Abiquiu Reservoir*.

Date	Interval d	Mean Flow** $m^3d^{-1}x10^3$	Total Flow m^3x10^3	Total Nitrogen kg	Total Phosphorus kg
5-30-78	8	4035.9	32,287.2	25,668.3	5,844.0
6-13-78	24	2376.0	57,024.0	48,185.3	3,877.6
7-19-78	30	933.0	27,990.0	71,654.4	5,122.2
8-10-78	45	1020.7	45,931.5	71,882.8	5,236.2
10-17-78	100	382.0	38,200.0	13,370.0	1,451.6
2-27-79	84	317.6	26,678.4	12,005.3	2,854.6
4-03-79	25	1935.4	48,385.0	30,676.1	13,354.3
4-18-79	12	4952.3	59,427.6	73,987.4	28,347.0
4-28-79	14	6033.0	84,462.0	76,860.4	22,635.8
5-15-79	20	5729.1	114,582.0	92,238.5	23,947.6
6-06-79	17	5648.3	96,021.1	102,262.5	22,084.9
6-19-79	17	3404.3	57,873.1	10,995.9	10,880.1
7-10-79	25	1174.4	29,360.0	4,844.4	4,638.9
8-08-79	15	273.4	4,101.0	-	299.4

* Nutrient concentrations measured on the indicated dates were used to estimate concentrations for the intervals between sample collections.

** Data obtained from Albuquerque District, Corps of Engineers.

Table 59. Outflow volumes and total nitrogen and total phosphorus released from Abiquiu Reservoir*.

Date	Interval d	Mean Flow** $m^3d^{-1}x10^3$	Total Flow m^3x10^3	Total Nitrogen kg	Total Phosphorus kg
4-04-78	28	1070.1	29,962.8	11,835.3	-
5-30-78	53	3537.4	187,482.2	106,864.9	28,872.3
7-19-78	32	1743.9	55,804.8	28,460.4	13,337.3
8-04-78	46	1139.9	52,435.4	26,479.9	4,719.2
10-17-78	54	367.4	19,839.6	13,490.9	1,904.6
11-21-78	66	349.3	23,053.8	8,760.4	1,682.9
2-27-79	58	257.6	14,940.8	7,171.6	956.2
3-16-79	17	997.0	16,949.0	26,101.5	-
4-03-79	17	2269.6	38,583.2	26,892.5	2,932.3
4-18-79	12	3303.2	39,638.4	20,612.0	5,034.1
4-28-79	14	3872.6	54,216.4	39,578.0	5,963.8
5-15-79	13	4370.5	56,816.5	30,112.7	8,067.9
5-24-79	11	2581.6	28,397.6	14,908.7	6,105.5
6-06-79	13	2354.2	30,604.6	22,647.4	8,477.5
6-19-79	17	2473.8	42,054.6	7,780.1	11,354.7
7-10-79	25	2386.2	59,655.0	9,544.8	7,098.9
8-08-79	15	323.4	4,851.0	-	679.1

* Nutrient concentrations measured on the indicated dates were used to estimate concentrations for the intervals between sample collections.

** Data obtained from Albuquerque District, Corps of Engineers.

Table 60. Water and nutrient balance for Abiquiu Reservior for 7-25-78 to 7-24-79.

	Water $m^3 x10^3$	Nitrogen kg	Phosphorus kg	Nitrogen mg/l	Phosphorus mg/l	N/P
Inflow (1)	602,992.9*	494,428	135,810	0.820	0.225	3.64
Outflow (2)	478,865.7	254,938	65,886	0.532	0.138	3.86
Storage 7-25-78	30,603	19,953	2,142	0.652	0.070	9.31
Storage 7-24-79	148,079	33,170	7,256	0.224	0.049	4.57
Change in Storage (3)	+117,476	+13,216	+5,114			
Retention (4)=(1)-(2)-(3)	6,651.2	226,274	64,811			
% Retention $\frac{(4)}{(1)}X100$	1.10	45.8	47.7			

*Inflow was 602,992,900 m^3 during the indicated period.

period of greatest runoff in the spring of 1979 (Table 56, Figure 16). Nitrogen concentration also increased during the spring runoff in 1979; however, the concentration of this nutrient was considerably below that measured during the summer of 1978. The ratio of nitrogen to phosphorus in influent water was quite low (< 4.7) except for the period of June - October 1978 when it ranged from 9.2 to 14.

The concentration of nitrogen and phosphorus in the outflow from Abiquiu Reservoir was less variable than in the inflow; however, an unusually high nitrogen concentration was measured in March, 1979 (Table 57, Figure 17). The concentration of phosphorus in the effluent increased during periods of rapid flow and this is especially evident during and following the spring of 1979. The nitrogen-to-phosphorus ratio was generally quite low and decreased below a ratio of 4 in the period of May - July 1979. Total nutrient exchange at either the inlet or outlet is by far the greatest during periods of rapid flow, i.e., spring runoff, because not only of increases in flow of more than an order of magnitude, but also of higher nutrient concentrations compared to periods of minimal flow.

Nutrient balance calculations for Abiquiu Reservoir indicate that 46% of the nitrogen and 48% of the phosphorus entering the reservoir was retained when corrections are made for increased water and suspended nutrient storage in the reservoir in July 1979 (Table 60). Weighted mean nitrogen and phosphorus concentrations decrease accordingly from the inlet to the outlet. The overall tendency for nitrogen limitation relative to phosphorus is indicated by mean nitrogen to phosphorus ratios of 3.64 and 3.86 in the inflowing and outflowing waters respectively during the nutrient balance study.

Based on typical water storage of 25,000 acre-feet and a surface area of 893 acres (U.S. Army Corps of Engineers, 1975), surface loading of nitrogen and phosphorus occurred at 137 and 37.6 g $m^{-2}yr^{-1}$. While these loading rates are extremely high (Vollenweider, 1968), their impact would be minimized by the rapid flux of water through Abiquiu Reservoir. If Abiquiu Reservoir had been maintained at 25,000 acre-feet during the year of this nutrient balance study, the average water retention time would have been 18.7 days, corresponding to water turnover of 20 times per year.

The total nitrogen and total phosphorus concentrations, nitrogen phosphorus ratios, and daily flow rates at the Cochiti inlet (U.S. Geological Survey gauging station at Otowi Bridge) and outlet are given in tables 61 and 62. Total nutrient concentrations and average monthly inflow and outflow rates are shown in figures 18 and 19. The total volume of water, total nitrogen, and total phosphorus entering and released from Cochiti Reservoir were calculated from daily flow rates and nutrient concentrations and are tabulated in tables 63 and 64. Nitrogen, phosphorus and water balances for Cochiti Reservoir were calculated for the periods of March 15, 1978 to March 14, 1979 and July 11, 1978 to July 10, 1979 representing a spring of well below average runoff (1978) and a spring of record high runoff (1979) from the Rio Grande System (Table 65).

Highest concentrations of nitrogen in influent waters were measured in the late spring and summer of 1978 (Figure 16, Table 61). Nitrogen concentrations decreased in the winter and then increased with the beginning of the spring runoff in 1979; however, the nitrogen concentration decreased sharply in May and June when runoff was at a maximum. Phosphorus concentrations likewise increased from low winter values with the beginning

Table 61. Nitrogen and phosphorus concentrations, nitrogen phosphorus ratios, and inflow volumes at the Cochiti inlet.

Date	Nitrogen mg/l	Phosphorus mg/l	N/P	Inflow* CFS
3-15-78	0.670 ± .000**	0.207	3.24	610
5-30-78	1.925 ± .587	0.136 ± .066	14.2	2743
7-19-78	3.155 ± .460	0.227 ± .016	13.9	1112
8-10-78	3.425 ± .290	0.068	50.4	945
10-17-78	0.435 ± .007	0.040 ± .002	10.9	240
11-21-78	0.285 ± .035	0.069 ± .000	4.13	564
2-27-79	0.530 ± .028	0.154 ± .008	3.44	645
3-16-79	1.175 ± .134	0.599 ± .000	1.96	1794
4-03-79	0.583 ± .040	0.178 + .008	3.28	1874
4-19-79	2.425 ± .007	0.464	5.23	5411
4-28-79	1.325 ± .148	0.436	3.04	6347
5-15-79	0.800 ± .028	0.274 ± .005	2.92	4263
6-06-79	0.835 ± .035	0.407 ± .008	2.05	7475
6-19-79	0.335 ± .120	0.364 ± .005	0.92	7448
7-10-79	0.060 ± .014	0.052 ± .023	1.15	4315

* Data obtained from Albuquerque District, Corps of Engineers.

** Standard deviation for duplicate samples collected in field.

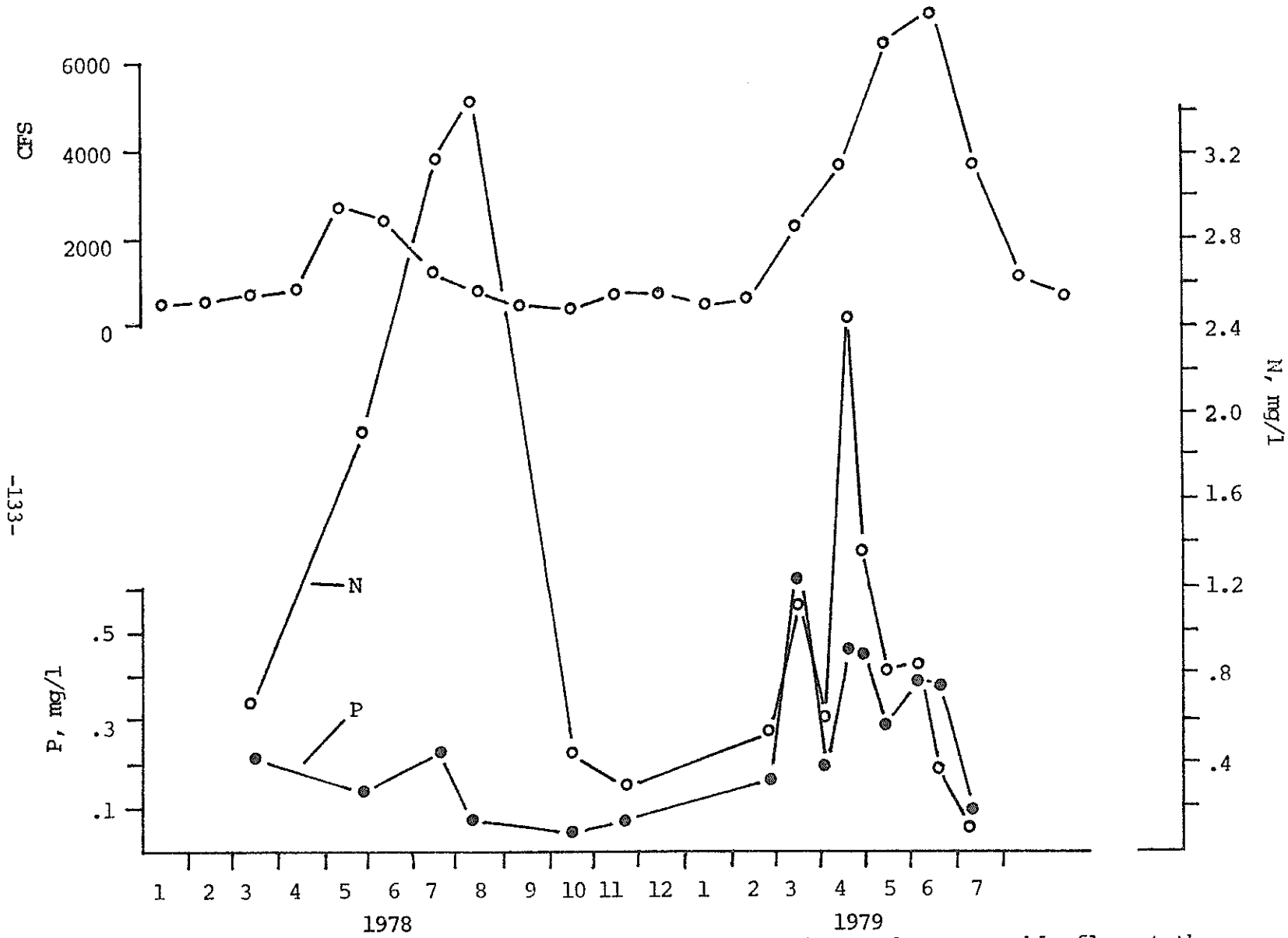

Figure 18. Total nitrogen and total phosphorus concentrations and mean monthly flow at the inlet of Cochiti Reservoir. CFS is cubic feet per second.

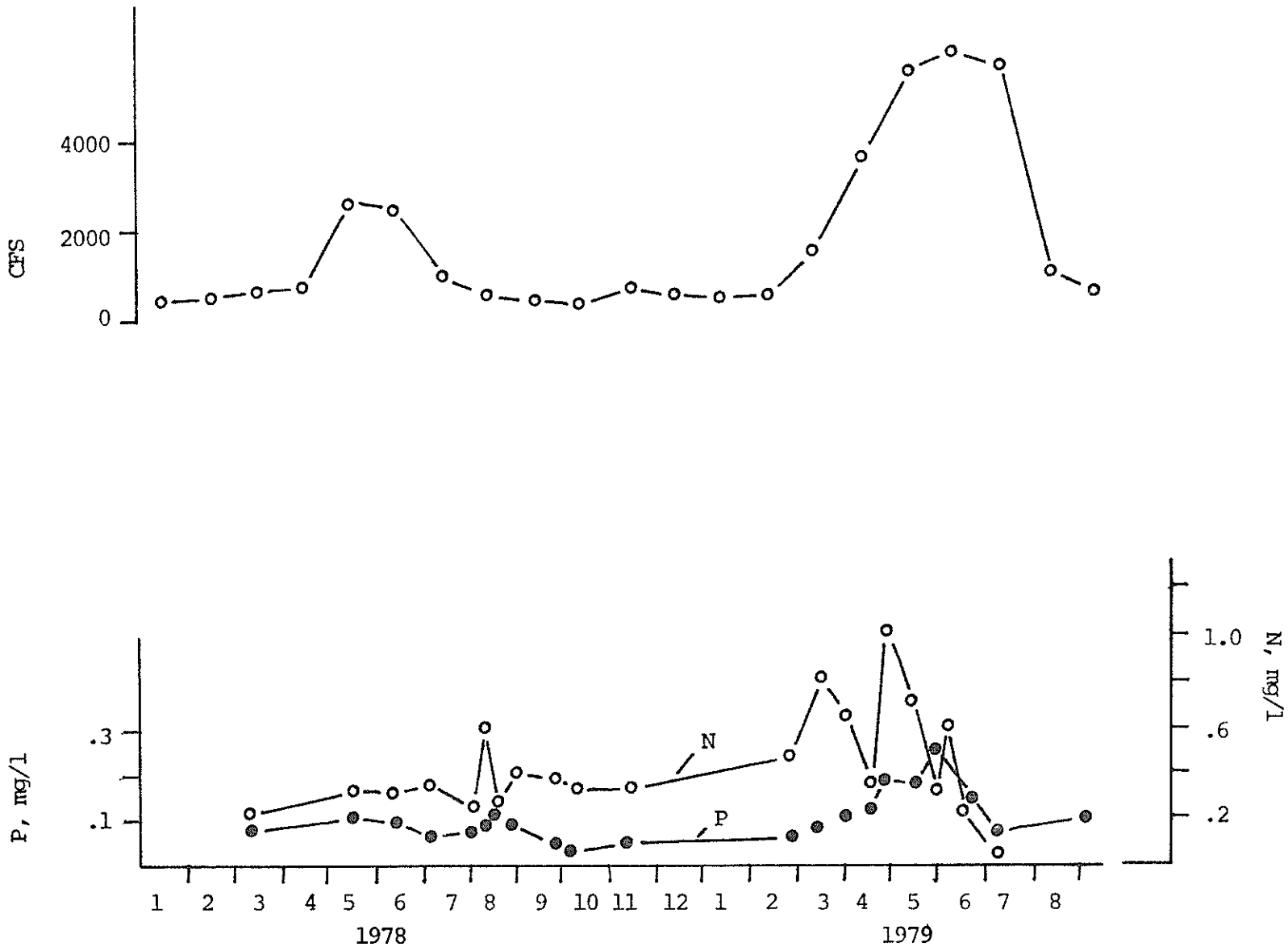

Figure 19. Total nitrogen and total phosphorus concentrations and mean monthly flow at the outlet of Cochiti Reservoir. CFS is cubic feet per second.

Table 62. Nitrogen and phosphorus concentrations, nitrogen phosphorus ratios, and outflow volumes at the Cochiti outlet.

Date	Nitrogen mg/l	Phosphorus mg/l	N/P	Outflow* CFS
3-09-78	0.225 ± .007**	0.086 ± .005	2.62	687
5-16-78	0.325 ± .007	0.106 ± .005	3.07	3092
6-13-78	0.327 ± .119	0.091 ± .001	3.59	2303
7-06-78	0.345 ± .021	0.063 ± .000	5.48	896
8-03-78	0.255 ± .007	0.072 ± .010	3.54	856
8-10-78	0.620 ± .028	0.084	7.38	707
8-17-78	0.280 ± .127	0.109 ± .000	2.57	262
8-29-78	0.405 ± .049	0.092 ± .010	4.40	186
9-28-78	0.385 ± .021	0.048 ± .000	8.02	512
10-07-78	0.345 ± .035	0.028 ± .000	12.3	254
11-14-78	0.330 ± .071	0.053 ± .003	6.23	608
2-27-79	0.480 ± .127	0.062 ± .019	7.74	652
3-16-79	0.805 ± .573	0.086 ± .005	9.36	2022
4-03-79	0.646 ± .016	0.104 ± .001	6.21	1998
4-19-79	0.330	0.126 ± .000	2.62	5232
4-28-79	1.025 ± .332	0.190 ± .010	5.39	5713
5-15-79	0.710 ± .226	0.180 ± .008	3.94	4712
5-31-79	0.305 ± .035	0.249 _ .086	1.22	6512
6-06-79	0.625 ± .007	0.213 ± .007	2.93	5955
6-19-79	0.235 ± .049	0.140 ± .007	1.68	6496
7-10-79	0.045 ± .064	0.069 ± .003	0.65	5970
9-07-79	-	0.094 ± .001	-	1412

* Data obtained from Albuquerque District, Corps of Engineers.

** Standard deviation.

Table 63. Inflow volumes and total nitrogen and total phosphorus entering Cochiti Reservoir*.

Date	Interval d	Mean Flow** $m^3d^{-1}X10^3$	Total Flow m^3X10^3	Total Nitrogen kg	Total Phosphorus kg
3-15-78	38	1,586.7	60,294.6	40,397.4	8,362.3
5-30-78	64	5,828.7	373,036.8	718,095.8	50,733.0
7-19-78	36	3,011.1	108,399.6	342,000.7	77,634.2
7-10-78	49	1,535.8	75,254.2	257,745.6	5,117.3
10-17-78	47	1,076.9	50,614.3	22,017.2	2,024.6
11-21-78	62	1,564.7	97,011.4	27,648.2	6,693.8
2-27-79	66	1,386.1	91,482.6	48,485.8	14,088.3
3-16-79	17	4,421.7	75,168.9	88,323.5	45,026.2
4-03-79	17	5,332.1	90,645.7	52,846.4	16,134.9
4-19-79	12	10,187.1	122,245.2	296,444.6	56,721.8
4-28-79	13	14,382.8	186,976.4	247,743.7	81,521.7
5-15-79	20	15,245.3	304,906.0	243,924.8	83,544.2
6-06-79	17	20,552.3	349,389.1	291,739.9	142,201.4
6-19-79	18	16,172.9	291,112.2	97,522.6	105,964.8
7-10-79	10	11,943.7	119,437.0	7,166.2	6,210.7

*Nutrient concentrations measured on the indicated dates were used to estimate concentrations for the intervals between sample collections.

**Data obtained from Albuquerque District, Corps of Engineers.

Table 64. Outflow volumes and total nitrogen and total phosphorus released from Cochiti Reservoir*.

Date	Interval d	Mean Flow** $m^3d^{-1}X10^3$	Total Flow m^3X10^3	Total Nitrogen kg	Total Phosphorus kg
3-09-78	34	1,609.2	54,712.8	12,310.4	4,705.3
5-16-78	49	4,833.4	236,836.6	76,971.9	25,104.7
6-13-78	26	5,943.2	154,523.2	50,529.1	14,061.6
7-06-78	25	2,843.8	71,095.0	24,527.8	4,479.0
8-03-78	17	2,106.4	35,808.8	9,131.2	2,578.2
8-10-78	7	1,971.6	13,801.2	8,556.7	1,159.3
8-17-78	10	1,314.3	13,143.0	3,860.0	1,432.6
8-29-78	21	1,026.2	21,550.2	8,727.8	1,982.6
9-28-78	19	1,134.3	21,551.7	8,297.4	1,034.5
10-07-78	24	886.3	21,271.2	7,388.6	595.6
11-14-78	71	1,566.8	111,242.8	36,710.1	5,895.9
2-27-79	62	1,450.4	89,924.8	43,163.9	5,575.3
3-16-79	17	4,416.8	75,085.6	60,443.9	6,457.4
4-03-79	17	5,238.0	89,046.0	57,523.7	9,260.8
4-19-79	12	10,385.5	124,626.0	41,126.6	15,702.9
4-28-79	13	13,677.6	177,808.8	182,254.0	33,783.7
5-15-79	17	13,352.1	226,985.7	161,159.8	40,857.4
5-31-79	11	14,693.2	161,625.2	49,295.7	40,244.7
6-06-79	9	14,452.7	130,074.3	81,296.4	27,705.8
6-19-79	18	15,393.0	277,074.0	65,112.4	38,790.4
7-10-79	10	14,523.6	145,236.0	6,535.6	10,021.3

*Nutrient concentrations measured on the indicated dates were used to estimate concentrations for the intervals between sample collections.

**Data obtained from Albuquerque District, Corps of Engineers.

Table 65. Water and nutrient balance for Cochiti Reservior.
3-15-78 to 3-14-79

	Water $m^3 x10^3$	Nitrogen kg	Phosphorus kg	Nitrogen mg/l	Phosphorus mg/l	N/P
Inflow (1)	878,782.5*	1,483,051	125,217	1.688	0.142	11.89
Outflow (2)	857,747.8	305,942	69,661	0.357	0.081	4.41
Storage 3-15-78	58,666.8	17,659	5,221	0.301	0.089	3.38
Storage 3-14-79	71,189.1	30,042	7,119	0.422	0.100	4.22
Change in Storage (3)	+12,522.3	+12,383	+1,898			
Retention (4)=(1)-(2)-(3)	8,512.4	1,164,726	53,658			
% Retention $\frac{(4)}{(1)}x100$	0.97	78.5	42.8			

7-11-78 to 7-10-79

	Water $m^3 x10^3$	Nitrogen kg	Phosphorus kg	Nitrogen mg/l	Phosphorus mg/l	N/P
Inflow (1)	1,901,632.6	1,831,124	576,007	0.963	0.303	3.18
Outflow (2)	1,758,471.4	838,386	244,503	0.477	0.139	3.43
Storage 7-11-78	64,978.5	26,706	4,678	0.411	0.072	5.71
Storage 7-10-79	189,215.8	14,002	20,624	0.074	0.109	0.68
Change in Storage (3)	+124,237.3	-12,704	+15,946			
Retention (4)=(1)-(2)-(3)	18,923.9	1,005,442	315,558			
% Retention $\frac{(4)}{(1)}x100$	1.00	54.9	54.8			

*Inflow was 878,782,500 m^3 for the indicated period.

of heavy spring runoff in 1979; however, phosphorus concentrations remained relatively high throughout the period of maximum runoff from March-June. The data for the two years suggest that the total phosphorus concentration increases as the sediment load increases at greater flow rates. The total nitrogen concentration also increases during spring runoff; however, it tends to be significantly diluted when runoff is very rapid as in the spring of 1979. Consequently the nitrogen-phosphorus ratio of influent water was relatively high (>10) in the spring and summer of 1978 and low (<5.3) in the spring and early summer of 1979. These observations are consistent with runoff transport of nitrogen as a constituent of organic material chiefly from on or near the surface of the soil while the phosphorus transported is largely inorganic soil mineral material which is transported at a concentration related to the sediment load. Thus the total nitrogen concentration is diluted while the concentration of phosphorus increases with erosion resulting from rapid runoff.

Total nitrogen and total phosphorus concentrations in effluent water were much less variable than in influent water (figures 18 and 19). The high concentration of total nitrogen measured at the inlet in the summer of 1978 was not detected at the outlet, probably because of biological utilization within the reservoir. Nitrogen phosphorus ratios at the outlet, in contrast to the inlet, were low (2.6 - 8.0) throughout the summer of 1978. Some increase in the total nitrogen and phosphorus concentrations at the outlet occurred during the heavy runoff in the spring of 1979 as a result of rapid movement of water through the reservoir bearing a heavy sediment load while biological utilization of nutrients

was limited by severely restricted light penetration and lower than normal spring water temperatures (see tables 3 and 5).

Nutrient balance calculations including the spring of 1978, characterized by below average runoff, indicated that 78% of the nitrogen and 43% of the phosphorus entering the reservoir were retained (Table 65). In the spring of unusually high runoff (1979) 55% of both these nutrients were retained in the reservoir. These latter values do not differ greatly from those computed for Abiquiu Reservoir during the same year (Table 60). All these values fall within the ranges compiled by Vollenweider (1968) for a number of diverse lakes. The greater retention of nitrogen during a year of below average runoff than during a year of unusually high runoff possibly may be attributed to increased biological utilization of nitrogen by phytoplankton under conditions of greater light penetration associated with a limited sediment load. Additionally, nitrogen utilization by submersed and emergent macrophytes would be much greater under the conditions of relatively constant water storage occurring in the 1978 growing season. In 1979, water storage increased from a minimum of 47,252 acre-feet on May 16, 1979 to a maximum of 184,370 acre-feet on June 21, 1979. The rapid increase in water storage was extremely destructive to both submersed and emergent macrophytes due to greatly decreased light penetration and habitat destruction. Conditions favoring greater biological utilization of nitrogen would increase retention of nitrogen in plant biomass and concomitantly a lower flushing rate would favor increased transfer of organic material to the sediments. Phosphorus is relatively abundant in Cochiti Reservoir and its retention apparently was not affected in a similar manner by the differing hydrological and biological conditions in these two years.

Based on storage of 55,000 acre-feet and a surface area of 1,330 acres (U.S. Army Corps of Engineers, 1974) surface loading of nitrogen and phosphorus were estimated to be 276 and 23.3 g/m^2 for the twelve months following March 1978 with 340 and 107 g/m^2 in the twelve months following July 1978. As previously indicated the rapid flushing of water through the reservoir greatly reduces the impact of the extremely high nutrient load. If a storage volume of 55,000 acre-feet were maintained, water in Cochiti Reservoir would be exchanged 13 and 28 times respectively in twelve months following March 1978 or July 1978.

Most nitrogen retained in sediments in lakes or reservoirs is permanently lost by denitrification (Vollenweider, 1968). Phosphorus, however, may be redissolved from anaerobic sediments and, depending on lake depth and currents, recycled (Vollenweider, 1968). The significance of phosphorus recycling is unknown in Cochiti and Abiquiu reservoirs.

CONCLUSIONS

Evaluation of chemical parameters

Nutrient loading

Aquatic biologists have considered nitrogen and phosphorus as causative nutrients in eutrophication responsible for algal blooms. In the United States and elsewhere, phosphorus is most commonly in critical supply and the more refined nutrient loading models have been based on inputs of this nutrient. Our bioassays have indicated at various times that nitrogen, phosphorus and iron, singly or in combination, are limiting for both green algae and cyanobacteria in Abiquiu and Cochiti reservoirs. The frequent abundance of phosphorus relative to nitrogen is indicated by the low nitrogen-to-phosphorus ratios measured through most of our studies. Thus the existing phosphorus loading models would not be expected to be applicable to Abiquiu or Cochiti reservoirs. In additon, nutrient loading models assume steady state storage conditions and have been developed for lakes with limited flushing rates. There is a serious need for development of nutrient loading models for lakes with nitrogen and iron as limiting nutrients as well as for lakes with high flushing rates (e.g., 10-30 water exchanges per year as occur in Abiquiu and Cochiti reservoirs).

Nutrient recycling

The recycling of nutrients from sediments is of greater importance with phosphorus than nitrogen because nitrogen is readily lost from the sediments by denitification (Vollenweider, 1968) and additionally, cyanobacteria can fix dinitrogen. The two major activities involved in recycling of phosphorus are enzymatic cleavage of phosphate compounds from organic polymers and

solubilization of precipitated inorganic phosphates. Both of these activities are accomplished by anaerobic bacteria. The limiting factor for the anaerobic movement of phosphate is often the quantity of available organic material which is used by bacteria as the energy source. The depth of sediments at this time is not very great at either reservoir due to the recent draining at Abiquiu and the recent establishment of Cochiti Reservoir. Perhaps one would attempt to dismiss the anaerobic processes in the sediments on the basis of the lack of fermentable carbon sources; however, on numerous occasions gas evolution was observed in the water of the upper channel of Cochiti Reservoir. The downward movement of phytoplankton to the bottom of the reservoir would provide a sufficient nutrient source for anaerobic bacteria.

Iron

The availability of Fe^{3+} to phytoplankton is of great importance in alkaline lakes and reservoirs. Bacteria (including cyanobacteria) elaborate chelators which sequester iron and this chelated iron is taken up by the bacteria. Metabolism of iron would follow the intracellualr release of the iron atom from the chelator. Since bacteria are able to use a wide range of molecular types of iron chelators, the cyanobacteria would be able to use iron chelators produced by a variety of aquatic bacteria. Diatoms and other types of algae would not be able to utilize the iron chelators of bacterial origin but would use iron by an alternate process which would be in competition with the bacterial chelator system. Iron chelation has been suggested as a key in the dominance of cyanobacteria (blue-green algae) over true algae in aquatic environments (Murphy et al., 1976). Further research is required to clarify the role of iron chelation in aquatic ecosystems.

Iron is often a limiting micronutrient in Cochiti Reservoir as determined from the radio-iron experiments and from both laboratory and *in situ* bioassays. The low level of available iron coupled with other environmental factors apparently would contribute to the absence of winter-spring diatom blooms. Diatom blooms occur in many lakes and are desirable because they would in part contribute to the control of cyanobacterial blooms by depletion of avaiable nutrients.

Radioactive compounds

In north central New Mexico, rich deposits of heavy metals including uranium occur. Abiquiu Reservoir is in fact constructed on a geological formation which may contain very low levels of uranium. It is unfortunate that radioactivity was not determined in fish, sediments and water from Abiquiu and Cochiti reservoirs. Certainly this should be one of the priorities of a future study.

Algal activities

Trophic status and overall trends

Based on nutrient and phytoplankton studies, we previously classified Abiquiu Reservoir as mesotrophic (1976-77) and Cochiti Reservoir as eutrophic and mesotrophic, in 1976 and 1977 respectively (Barton and Johnson, 1978). Small blooms occurred in Abiquiu Reservoir during 1978 and in Cochiti Reservoir during September 1979. Although we have received reports from U.S. Army Corps of Engineers personnel of massive blooms in the upper channel of Cochiti Reservoir, we did not document this activity because these blooms were a kilometer or more above our sampling stations. The blooms on the main body of Cochiti Reservoir were of smaller magnitude during 197-1979 than those we reported in 1976 when the reservoir was first filled. Although the

total nitrogen concentration in Cochiti Reservoir decreased after 1976, nutrient concentrations in the reservoirs have not further decreased and we expect occasional nuisance blooms to occur in these reservoirs in the future. Perhaps both of these reservoirs would be best categorized as being meso-eutrophic.

Significance of nitrogen fixation

While nitrogen fixation contributes negligibly to the overall nitrogen budget of Abiquiu and Cochiti reservoirs, the low nitrogen-to-phosphorus ratio of the water strongly favors nitrogen-fixing cyanobacteria. After the massive nutrient input of spring runoff, nutrient concentrations as well as influent volume is greatly reduced. In 1979, the nitrogen-to-phosphorus ratio also decreased strikingly in the influent waters during the summer. Hence, nitrogen fixation is crucial to the development of large phytoplankton populations. Thus, some control of cyanobacterial blooms might be achieved by addition of low levels of $CuSO_4$ as an inhibitor of nitrogen fixation in limited areas where blooms are particularly undesirable because of esthetic and/or public health considerations (Horne and Goldman, 1974).

Control Practices

Water management

The occurrence of a cyanobacterial bloom in Cochiti Reservoir in the late summer of 1979, while not in Abiquiu Reservoir, raises questions about differences in water management and the incidence of blooms. Water was rapidly released from Cochiti Reservoir returning it to usual pool size while water was more slowly released from Abiquiu Reservoir and storage remained at an unusually high level throughout the summer of 1979. As lake depth increases the impact of excessive nutrient loading on eutrophication and the

resulting algal blooms decrease as the surface-to-volume ratio is reduced and a greater proportion of the nutrients are below the euphotic zone. Rapid movement of water through a lake increases the circulation of a limited nutrient in the euphotic zone as well as favoring recycling of nutrients present in bottom sediments as a result of increased currents. Thus, water management programs should be considered in relation to their impact on algal blooms as well as the traditional objectives of water management.

Land management

With the watersheds for the reservoirs being low in nutrients, any addition of nutrients due to recreational use becomes important. At Cochiti Reservoir, the amount of open water is rather small, certainly smaller than for Abiquiu, and the recreational use is concentrated in one area along the open water. Most reservoirs or lakes, like Abiquiu Reservoir, have the boat landing and shore activities along a long shoreline. In the absence of the long shoreline to buffer the land use, reservoirs would receive the full impact from recreation in a localized area. The site of the boat mooring facilities at Cochiti Reservoir contributes to the concern for water quality at Cochiti since it is located where recreation activity is greatest and because there is limited water circulation through this part of the reservoir. Multiple sites for shore use at Cochiti Reservoir and especially the development of the boat landing area on the east side of the reservoir should be considered.

Management and bloom control

A variety of management techniques have been examined to determine which measures are useful to control nuisance phytoplankton growing in lakes and reservoirs. In a report by Janik, Taylor and Barko (1980), management

techniques for improving water quality have been reviewed and techniques employed have incluced the following:

1. Biological control of phytoplankton through the use of: viruses and bacteria which are pathogenic for the phytoplankton; (b) protozoa, zooplankton and fish which exhibit grazing and predation activity; and (c) growth inhibitors, allelopathic compounds, mild acidification and silica addition as agents of biomanipulation.
2. Chemical control of phytoplankton through the addition of Cu, Zn, Cd and other toxic heavy metals; and (b) the inhibition of photosynthetic activity with herbicides.
3. Physical control of phytoplankton by: (a) the use of microstrainers and other harvesting methods to remove phytoplankton; (b) the addition of a coloring agent to water to reduce light penetration; and (c) lake drawdown, dredging of the bottom, increased rate of water discharge, artificial destratification and use of explosive charges. These physical control methods have been used singularly or in conjunction with other methods.

Often it has been difficult to evaluate the long-term benefits of these management practivces. In general, the following conclusions can be drawn about these techniques as they apply to Abiquiu and Cochiti reservoirs.

1. Copper sulfate and herbicides such as Aquazine or paraquat additions would produce only short-term benefits and would require additions to be made at the time of the bloom.
2. Many heavy metal compounds (i.e., silver, zinc, chromium, lanthanum, cadmium) would be very toxic to the environment and prohibitively expensive.

3. The chemistry of the water, especially the hardness, reduces the effectiveness of the algicides.

4. Control of cyanobacterial blooms through the use of invertebrate predators or virus activity would be inefficient.

5. Physical removal of phytoplankton is not economically practical.

Perhaps some of the best possibilities of nuisance phytoplankton control at Abiquiu and Cochiti reservoirs would include:

1. The reduction of nutrient inputs into the reservoirs through erosion control and improvement of sewage treatment facilities,

2. The addition of silica in early spring would support diatom growth followed by localized addition of copper sulfate or algicides when needed to reduce growth of cyanobacteria,

3. The use of specific bacteria to destroy cyanobacteria may be of considerable promise because it would constitute a natural control system, and

4. The introduction of an appropriate species of grasing fish, such as gizzard shad, should be considered.

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