PHYSICOCHEMICAL LIMNOLOGY AND COMMUNITY METABOLISM OF KEYSTONE RESERVOIR, OKLAHOMA

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METABOLISM OF KEYSTONE RESERVOIR,
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PREFACE

The objectives of this study were to: (1) compare physicochemical limnology of Keystone Reservoir during 1965-66 to 1966-67; (2) determine the effects of a change in level of reservoir discharge on intensity of stratification and circulation patterns; (3) determine the effects of impoundment on water quality; (4) estimate the heat, phosphorus, and oxygen budgets of the Cimarron arm; (5) estimate spatial and temporal variations in the rate of community metabolism of the Cimarron arm; and (6) evaluate the O_2 curve method as a means of estimating community metabolism of reservoirs.

Conclusions drawn from data obtained over a 12- to 24-month period may not be indicative of the long-term limnology of Keystone Reservoir but should be useful as a guide for future studies. The scope of this study prohibited extensive investigation of many aspects of the limnology of the reservoir. An effort was made to obtain a wide range of limnological data during the second and third years of impoundment to provide a baseline for future studies on the effects of reservoir aging.

Dr. Troy C. Dorris served as major adviser. Drs. Calvin G. Beames, Rudolph J. Miller, Robert D. Morrison, and Jerry L. Wilhm served on the advisory committee and patiently read the manuscript. Fred L. Spangler made all pigment analyses and part of the temperature and conductivity measurements during 1966-67. Associates of the Aquatic Biology Lab of

Oklahoma State University helped make field collections. Max M. McKee and David G. Simpson of the Oklahoma State University Computer Center assisted with programming. Henry Magalit of the Oklahoma State University Statistical Laboratory assisted with statistical analyses. Darrel L. Haston and Mac Crank helped with the drawings, and Mrs. Thomas Lee typed the final manuscript. The generous assistance of all of these people is appreciated. Special gratitude is due to Gary Rice for helping with field collections, providing technical advice on chemical analyses, and conscientiously assisting with laboratory analyses. Special thanks is extended to my wife, Judy, who assisted with calculations and typing and provided encouragement and understanding throughout the study.

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

Presently, over 1,000 reservoirs exist in the U. S. with a total storage capacity of approximately 360 million acre-feet (Woodbury 1967, Frey 1967). The total acreage is increasing at the rate of about 3.5% per year through construction of new reservoirs. The U. S. Bureau of Reclamation estimates that by the turn of the century the plains states alone will require more than 170 million acre-feet of water for irrigation of farmlands and that municipal and industrial water needs will be approximately 240 million acre-feet of water (Dominy 1967). Of the 240 trillion gallons of water presently used each day in the U. S., about 80% is returned to our rivers and streams. The 5-year cost of additional treatment of this water to meet the new water quality standards is estimated at $26 to $29 billion (Sanders 1968).

One of the chief problems in reservoir management and of the total management of watersheds containing reservoirs is the control of water quality so that use and subsequent re-use will not be impaired unduly by costs of treatment (Frey 1967). To solve this problem we need to understand the consequences of various management regimes and ways in which the regimes might be modified to maximize chemical and biological benefits in terms of water quality. Frey (1967) stated that we need long-term "complex" studies on a variety of types of reservoirs and that the relative lack of continuing intensive studies on particular reservoirs is the greatest deficiency of the reservoir research program in the U. S. as compared to the program of the Soviet Union. The literature review and statement of research needs by Symons, Weibel, and Robeck (1964) reveal an acute awareness of the need for comprehensive, continuous studies of the effects of impoundment on water quality.

The Reservoir Research Center of Oklahoma State University initiated a continuous, long-term study of the physicochemical limnology and community structure and function of Keystone Reservoir in June 1965. Keystone Reservoir was chemically stratified during all seasons of 1965-66 (Eley, Carter, and Dorris 1967), and stratification was only upset by large floods (Carter and Eley 1967). Physicochemical conditions influenced benthic community structure, with species diversity decreasing in deeper waters which had low concentrations of dissolved oxygen and high conductivity (Ransom 1969). Decreases in concentrations of chlorophylls and carotenoids downstream and with depth indicated that physicochemical conditions also caused spatial variations in plankton community structure (Spangler 1969). Concentrations of organic compounds collected by the carbon-absorption method were higher in the Arkansas arm than in the Cimarron arm of Keystone Reservoir, and concentrations of organics in Keystone were higher than most published values from other waters (Burks 1969). Falls (1969) investigated chemical equilibria in Keystone Reservoir and concluded that concentrations of the major dissolved inorganic chemical components could be duplicated by a 10 point equilibrium model. The model was based on the hypothesis that waters originally in equilibrium with the common evaporite and clay minerals in large areas of the Great Plains were diluted by fresher waters not exposed to the evaporite minerals as they flowed toward the reservoir.

The present study was designed to obtain basic data on the physicochemical limnology and community metabolism of Keystone Reservoir during the second and third years of impoundment.

CHAPTER II

KEYSTONE RESERVOIR, THE STUDY AREA

Keystone Reservoir, located on the eastern edge of the Great Plains, is part of the multiple-purpose Arkansas River Project (Fig. 1). The reservoir was formed by impounding the Arkansas River approximately 20 km upstream from Tulsa, Oklahoma, and was filled to power pool level (elevation 220 m Mean Sea Level) in April 1965. The impoundment was designed by the U. S. Army Corps of Engineers for flood control, hydroelectric power generation, recreation, and navigational purposes.

The two chief tributaries of the reservoir are the Arkansas and Cimarron Rivers which converge about 3 km above the dam to form the two main arms. The narrow, meandering arms follow the old channels of the Arkansas and Cimarron Rivers. The Arkansas arm flows generally in a northwest to a southeast direction and the Cimarron arm flows in a west-southwest to east-northeast direction. The reservoir has a surface area of 106.5×10^6 m^2 and a volume of 817.8×10^6 m^3 with a mean depth of 7.7 m and a maximum depth of 22.9 m at normal power pool level (220 m Mean Sea Level) (Table I). Water can be released from the reservoir through tainter or flood gates, sluice gates, or power penstocks which are 1.2, 20.1, and 21.5 m, respectively, below power pool level.

Numerous small creeks draining agricultural and woodland areas flow into the reservoir along both arms. Six towns ranging in

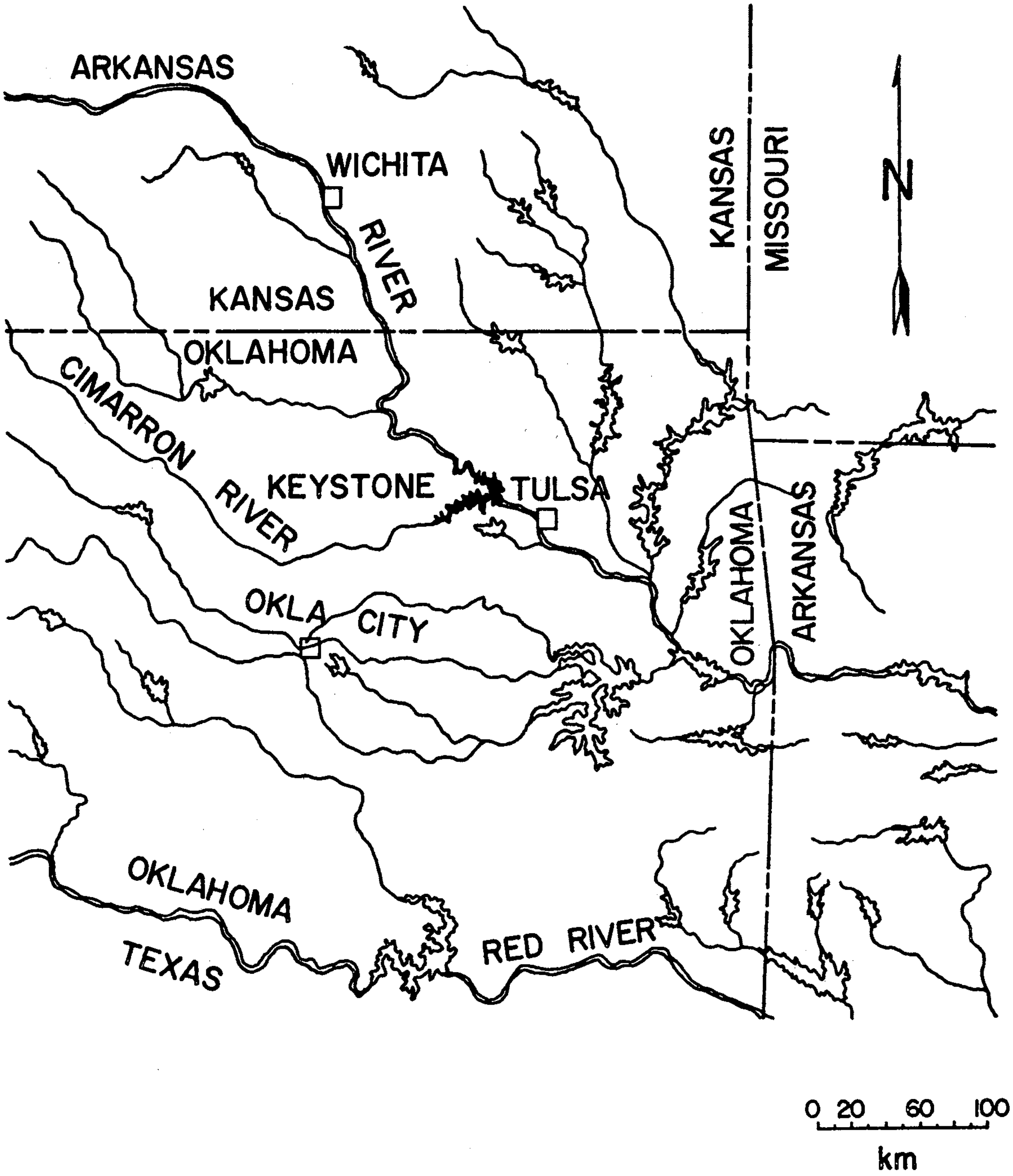

Figure 1. Location of Keystone Reservoir

population from 200 to 4,000 and several real estate developments are located on the shores of the reservoir. Housing developments use septic tanks for waste disposal. Towns use open bio-oxidation lagoons for sewage treatment. Overflow of lagoons during large rains and seepage from both lagoons and septic tanks probably contribute nutrients to the reservoir as well as to the ground water aquifer.

TABLE I

MORPHOMETRIC DATA OF KEYSTONE RESERVOIR

	Total	Cimarron Arm	Arkansas Arm
Total Drainage Area ($10^9 m^2$)	192.9	48.3	144.6
Contributing Drainage Area ($10^9 m^2$)	57.9	14.5	43.4
Surface Area* ($10^6 m^2$)	106.5	42.6	63.9
Volume* ($10^6 m^3$)	817.8	291.3	526.5
Mean Depth* ($\bar{Z}$ in m)	7.7	6.8	8.2
Maximum Depth* (Z in m)	22.9	20.4	22.9
Development of Volume ($\bar{Z}$/Z max)*	0.34	0.33	0.36

*At normal power pool level (220 m MSL) from records of the U. S. Army Corps of Engineers.

The Drainage Basin

The Arkansas and Cimarron river systems provide a total drainage area of 192.9 x 10^9 m^2 which extends from the Rocky Mountains in Colorado across southern Kansas and northern Oklahoma. The contributing drainage area of 57.9 x 10^9 m^2 produces an average annual flow in the Arkansas River at Tulsa of about 5.6 x 10^9 m^3 (Dover et al. 1968).

Most of the moisture in the drainage area is brought in by air currents moving northward from the Gulf of Mexico (Dover et al. 1968). Frontal-cyclonic rainfall is produced by moist air from the Gulf meeting cooler dry air masses moving southward from the continental interior. Convection rainfall caused by daytime heating also is an important type of precipitation. Average annual rainfall in the drainage basin ranges from above 41 cm in the High Plains in western Oklahoma to 80 cm in the east. There are considerable variations in seasonal and annual rainfall. Annual rainfall amounts during the period of this study ranged from 49.5 cm in 1966 to 81.2 cm in 1967 (Table II). Most of the annual precipitation occurs between April and September with May and June normally the wettest months of the year (Fig. 2). Winter is the dry season of the year with low precipitation in the drainage basin from October through March. The eastern edge of the basin has an average annual air temperature of about 15 C. Temperature changes are often rapid as is typical of a continental climate. Average monthly temperatures range from near 0 C in December, January, and February to near 30 C in June, July, and August.

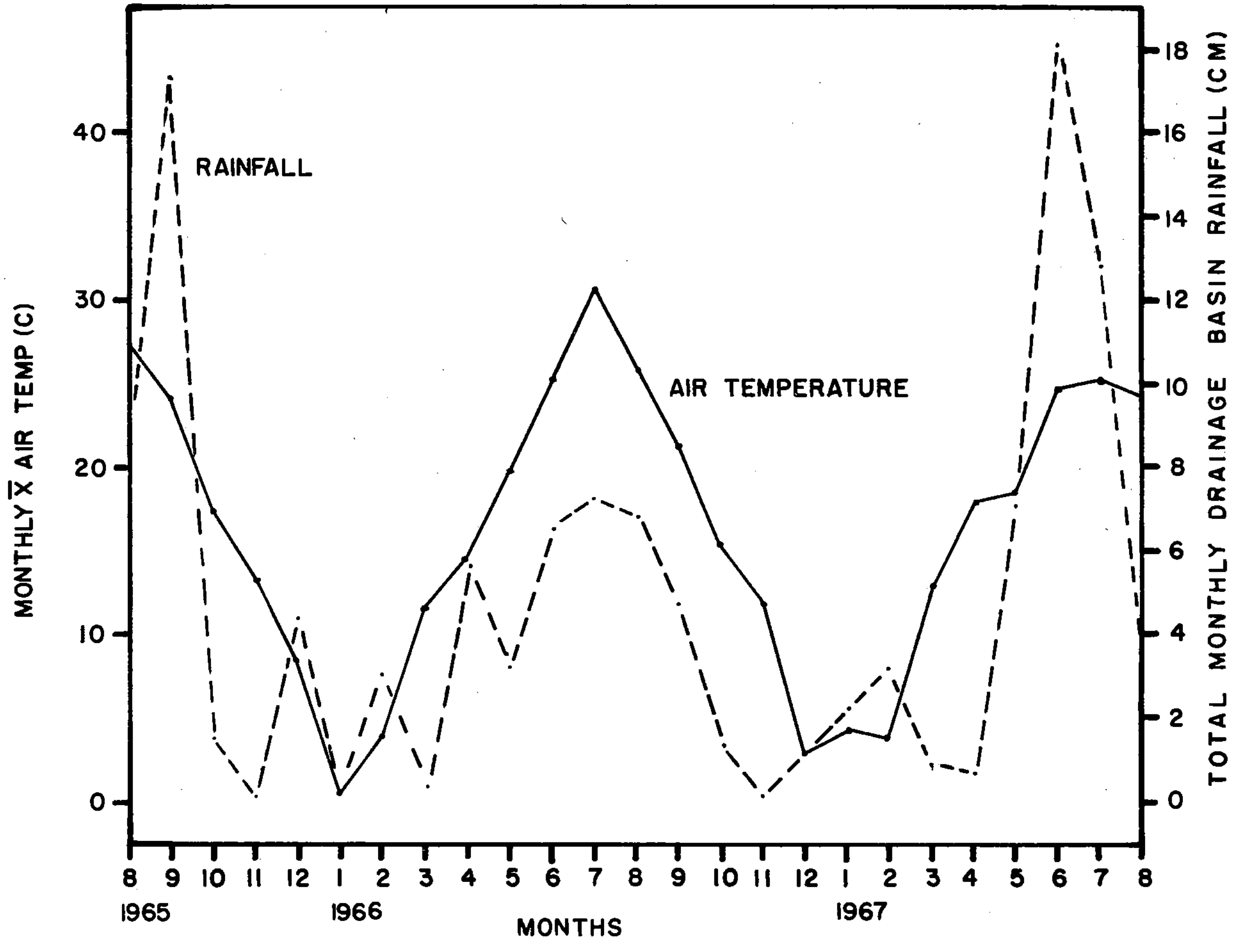

Figure 2. Drainage basin rainfall and air temperature during 1965-67 from records of U. S. Army Corps of Engineers and U. S. Weather Bureau

TABLE II

MEAN ANNUAL AIR TEMPERATURE AND PRECIPITATION FOR TULSA, OKLAHOMA, U. S. WEATHER BUREAU

	1965	1966	1967	$\bar{X}$
Mean air temperature (C)	16.0	14.8	14.8	15.2
Precipitation (cm)	62.2	49.5	81.2	64.3

Despite low precipitation and a high rate of evaporation in western parts of the drainage basin, nearly perennial flow in the Cimarron River is maintained by springs and seeps from a huge groundwater reservoir underlying the High Plains of western Oklahoma (Dover et al. 1968). Water from the principal aquifer, located in a layer of sand and gravel known as the High Plains deposit, is of the calcium-magnesium bicarbonate type with a total dissolved solids content of about 400 g m^{-3} and has a low sodium content, usually less than 25 g m^{-3}. Smaller aquifers located in alluvial deposits of the Cimarron River and smaller streams supply water of more erratic quality, often containing sulfate concentrations as high as 2,000 g m^{-3} and total dissolved solids exceeding 3,000 g m^{-3}. Despite these sources of highly mineralized water, water of the Cimarron River in the western part of the Oklahoma Panhandle is generally of good quality and is suitable for irrigation purposes.

The Cimarron River takes on entirely different characteristics as it flows through natural salt and gypsum deposits in the Permian redbeds of Harper, Woodward, Major, and Woods counties in western Oklahoma (Dover et al. 1968). The redbeds contain three massive layers of halite and gypsum. The Cimarron River in many places has eroded a channel 30 m deep into the bedrock. Ground water moving along fractures and joints in the Permian beds dissolve gypsum and halite and in places large springs of highly mineralized water, such as those in Roman Nose State Park, flow out. In Woods county, west of Freedom, Oklahoma, the Cimarron River at times is more highly mineralized than seawater, and the floodplain for several miles is covered with a thin layer of salt crystals. On low-flow days Cimarron River water south of Waynoka often contains 34,000 g NaCl m^{-3}.

North of the Cimarron River in western Oklahoma are sandy soils overlying an area of terrace deposits. The deposits provide a sizeable ground water reservoir of 7.5×10^6 m^3 km^{-2}. Water from this aquifer is of the calcium-magnesium bicarbonate type with a total dissolved solids concentration of 400 g m^{-3}. Ground water from this aquifer contributes to stream flow. The alluvium underlying the Cimarron River flood plain in western and central Oklahoma consists of sand and gravel 8 to 23 m in thickness, with water generally less than 6 m below the surface.

The Arkansas River originates in the Rocky Mountains near Leadville, Colorado, 1,500 km above the Oklahoma-Kansas state line. This reach of the river system drains an area of 120,000 km^2, and the average flow into Oklahoma is about 2.5×10^9 m^3 yr^{-1} (Dover et al. 1968). As the Arkansas River flows across the plains of Kansas, it receives large amounts of industrial and municipal effluents from Hutchinson and Wichita, Kansas, and from oil refineries in southcentral Kansas and northcentral Oklahoma. Quality of the incoming water is poor, with high concentrations of calcium and magnesium sulfate and sodium chloride. Ground water in the alluvium and terrace deposits along the Arkansas River in northcentral Oklahoma is of better quality than river water. Normally the water table in these deposits is sufficiently high to contribute to stream flow.

The first major tributary to the Arkansas River in Oklahoma is the Salt Fork River which makes its entrance near Ponca City. The stream rises in the gypsum hills of southern Kansas, and sulfate concentrations sometimes exceed 1,000 $g\ m^{-3}$ during periods of low flow. The river takes on a sodium chloride attribute as it flows through the natural salt plain just above Great Salt Plains Reservoir. Water from this reservoir usually does not have as high a salt concentration as the Cimarron River, but occasionally contains up to 7,000 $g\ NaCl\ m^{-3}$ (Dover et al. 1968). Water in the sand and gravel aquifer of the alluvium and terrace deposits along the Salt Fork is of the calcium sulfate type.

The Arkansas and Cimarron Rivers flow through areas of major oil and gas production, and the industry has drawn considerable attention as a major source of pollution. Occasionally oil-field brine pollution and oil spills occur, but in most instances these pollutants influence only local areas. Although industrial and municipal pollutants contribute to poor water quality in the drainage basin of Keystone Reservoir, salt deposits in northwestern Oklahoma are the dominant factors determining the composition and quality of these waters.

Water Balance of Keystone Reservoir, 1965-67

The water balance of a lake or reservoir is calculated by equating the rate of change in volume to the difference between the rate of water gain from all sources and the rate of water loss (Hutchinson 1957). Sources of income are inflow of drainage basin run-off, precipitation falling on the reservoir surface, and seepage into the reservoir basin. Drainage basin run-off is by far the most important source of water to main-stem reservoirs. This is also the case for most lakes, although some very large lakes, such as Lake Victoria, may receive most of their water as precipitation on the lake surface (Hutchinson 1957). The modes of loss of water from reservoirs are discharge of effluent through the dam, evaporation, and seepage from the reservoir basin. Most of the water loss from main-stem reservoirs is by discharge through the dam, while in many lakes evaporation or seepage are the primary modes of loss.

The water balance of Keystone Reservoir was calculated for each of the two years of this study (Table III). The first water year extended from 1 September 1965 through 31 August 1966. The second water year extended from 1 September 1966 through 31 August 1967. Of the calculated annual inflow, 69% was contributed by the Arkansas River, 17% by the Cimarron River, 10% by small streams tributary to the two main arms of the reservoir, and 2% by direct precipitation on the reservoir surface. Discharge through the dam accounted for about 96% of the calculated total outflow with loss by evaporation accounting for the remaining 4%. Estimates of the amount of seepage into or out of the reservoir were not available and were not included in calculating the water balance. Total outflow was computed by summing discharge and

TABLE III

WATER BALANCE OF KEYSTONE RESERVOIR

(All volumes x $10^6 m^3$)

	9/65 - 8/66	9/66 - 8/67	Average
Cimarron River Discharge	599.9	459.1	529.5
% of Total Inflow	17%	17%	17%
Arkansas River Discharge	2426.3	1911.5	2168.9
% of Total Inflow	70%	68%	69%
Inflow From Other Sources	401.0	364.1	382.5
% of Total Inflow	11%	13%	12%
Average Drainage Basin Precipitation (cm yr^{-1})	57.0	55.8	56.4
Contribution of Precipitation to Contributing Drainage Area	33,000	32,300	32,650
Contribution of Direct Precipitation	59.4	69.5	64.4
% of Total Inflow	2%	2%	2%
Reservoir Discharge	3383.8	2658.5	3021.2
Loss by Evaporation	135.1	121.1	128.2
% of Total Outflow	4%	4%	4%
Rate of Loss $m^3\ m^{-2} yr^{-1}$	1.27	1.14	1.20
Total Inflow	3486.6	2804.2	3145.3
Total Outflow	3518.9	2779.6	3149.4
Change in Storage Volume	-46.8	+34.5	Net = -12.3
Balance*	-14.5	+ 9.9	Net = - 4.6

*The balance which was unaccounted for by evaporation loss or change in storage can be attributed to a net error of 2% in making the various estimates when compared to total volume of the reservoir. Gains from or losses to ground water by seepage also may have contributed to this unaccountable balance. Data were derived from the records of the U. S. Geological Survey and U. S. Army Corps of Engineers. Cimarron River discharge was measured at Perkins, Oklahoma, and Arkansas River discharge was measured at Ralston, Oklahoma.

evaporation. Total inflow was computed by summing total outflow and net change in storage volume.

Inflows during 1965-66 averaged 110 m^3 sec^{-1} and were more erratic than inflows during 1966-67, which averaged 87 m^3 sec^{-1} (Fig. 3). Floodwaters entered the reservoir in September 1965 and in June 1967. The U. S. Army Corps of Engineers manipulated reservoir discharge to offset inflows and to maintain desired storage volume. During 1965-66, the normal pattern of storage manipulation was followed. Inflows exceeded outflows during the fall season causing an increase in storage volume during the dry winter months (Fig. 4). Outflows exceeded inflows during the early spring to provide additional storage capacity for anticipated floods during the wet season. During October and November 1966, large discharges were made to facilitate construction of a downstream navigation project and supplement hydro-power storage in downstream reservoirs. Water level dropped about 2.5 m resulting in a reduction in storage volume of over 200 x 10^6 m^3 (Fig. 4). During April and May 1967, the reservoir returned to normal power pool level. In June 1967, flood waters entered the reservoir and caused an increase in volume of 133 x 10^6 m^3 over normal storage volume.

Of the 32.6 x 10^9 m^3 of water which fell as precipitation on the contributing drainage area, only 3.1 x 10^9 m^3 entered the reservoir. This loss of 90% of the total drainage basin rainfall represents an average rate of evaporation and transpiration by plants in the drainage area of 0.5 m^3 m^{-2} yr^{-1}. About 85% of total precipitation in Oklahoma is lost by evaporation and transpiration (Dover et al. 1968). The average water loss by evaporation from the surface waters of Keystone Reservoir of 1.2 m^3 m^{-2} yr^{-1} appears to be a conservative estimate when

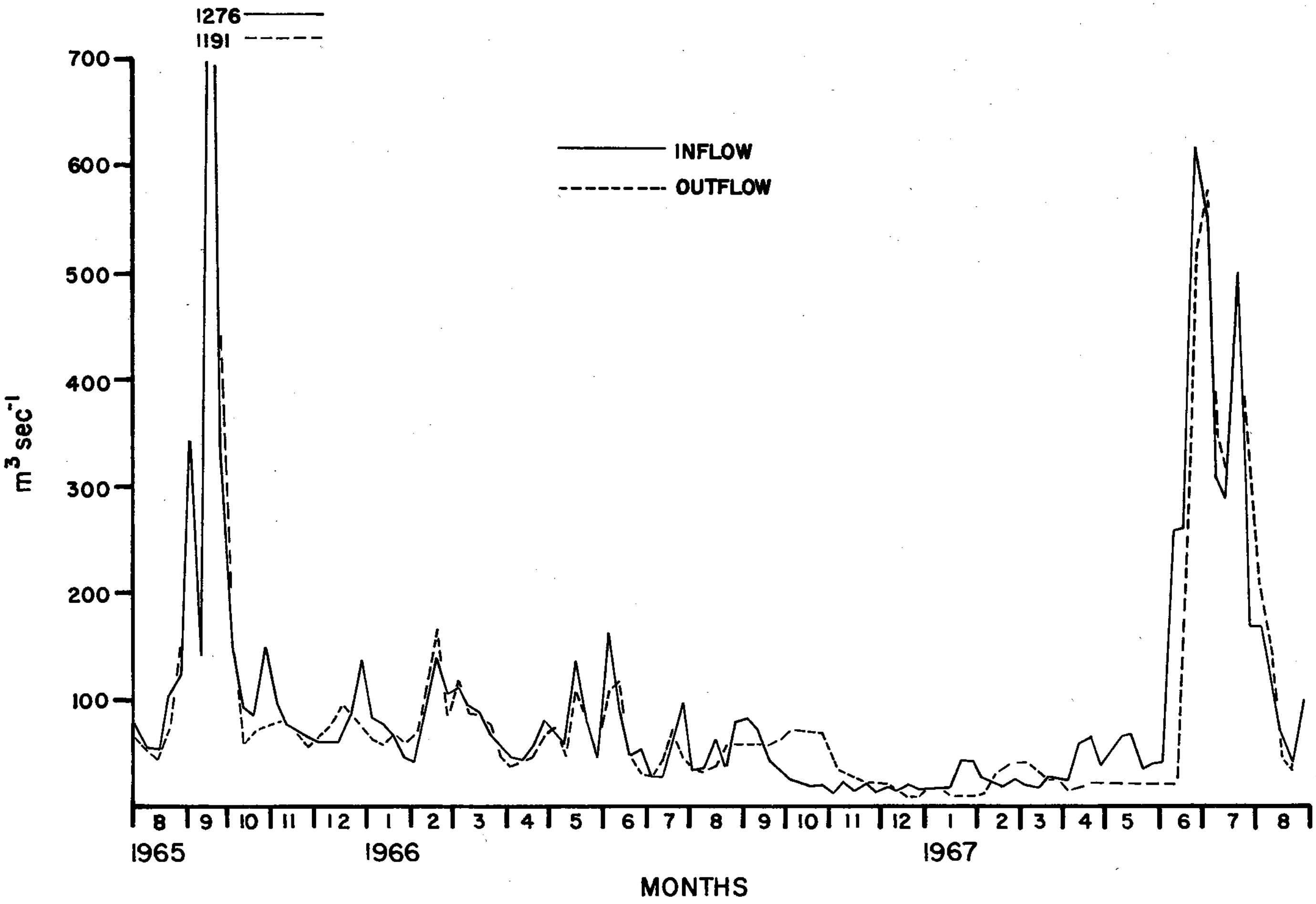

Figure 3. Temporal variations in total inflow and total outflow of Keystone Reservoir during 1965-67

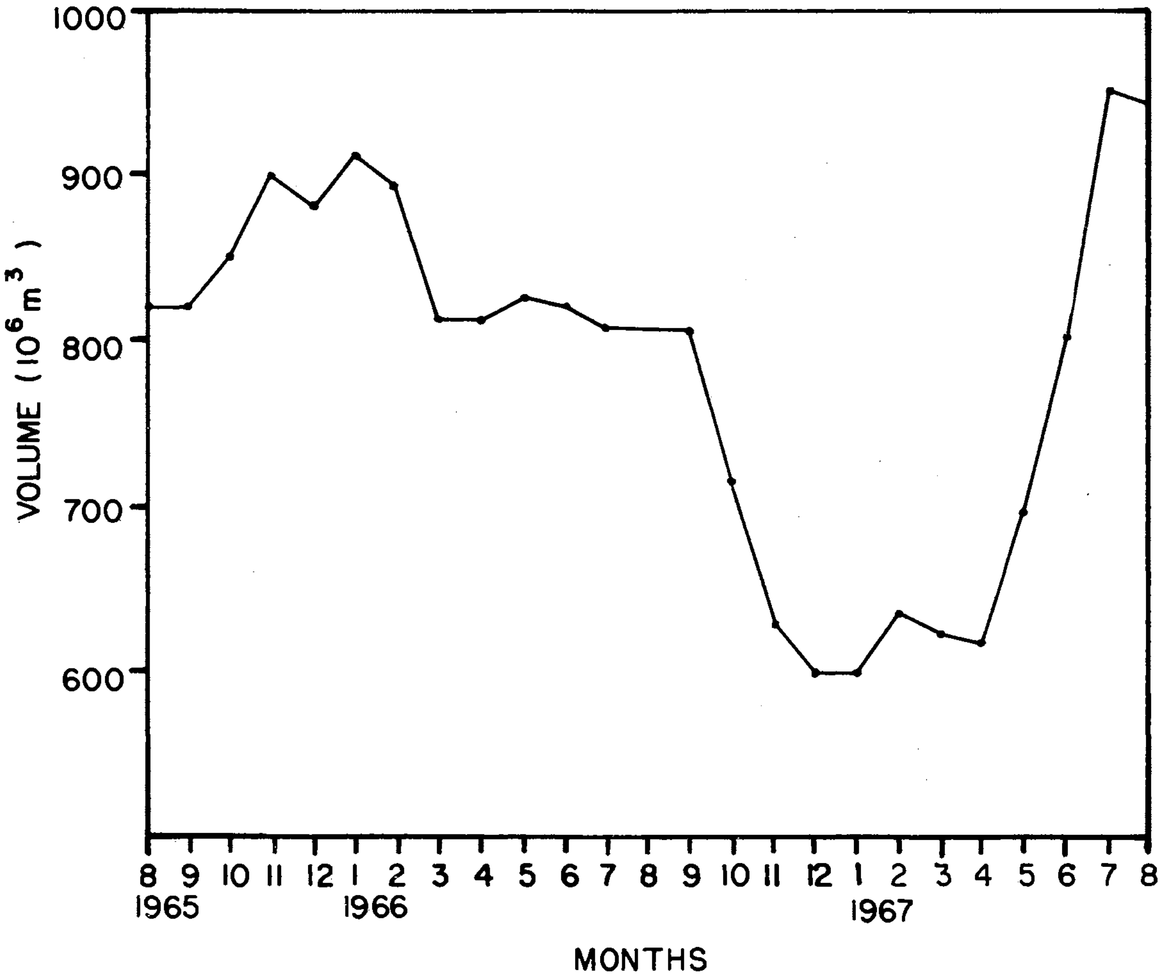

Figure 4. Temporal variations in the monthly average volume of Keystone Reservoir derived from records of the U. S. Army Corps of Engineers

compared with losses from Lake Mendota of 1.3 $m^3 m^{-2} yr^{-1}$ for 1948-49 and 0.9 $m^3 m^{-2} yr^{-1}$ for 1954-55 (Frey 1963), since the rate of evaporation in Wisconsin should be less than the rate of evaporation in Oklahoma.

Evaporation from surface waters of Keystone Reservoir showed notable seasonal variation (Fig. 5). Rates varied from less than 2 $m^3 sec^{-1}$ during the cool months of December, January, and February to greater than 6 $m^3 sec^{-1}$ during the warm months of June, July, and August. Rate of evaporation from surface waters of Keystone Reservoir averaged 4.3 $m^3 sec^{-1}$ in 1965-66 and 3.8 $m^3 sec^{-1}$ in 1966-67.

Sampling Areas

Four sampling areas in the Cimarron arm of the reservoir were selected for intensive study (Fig. 6). Occasional surveys of physicochemical conditions were made in the Arkansas arm of the reservoir. The study effort was concentrated on the Cimarron arm of the reservoir because the Cimarron River, although it contributes only about 17% of the total inflow, contains a concentration of dissolved solids about four times that of the Arkansas River and is a key factor in determining the stability of stratification in the reservoir (Eley et al. 1967).

Station I was located about 53 km above the dam at the point where the Cimarron River meets the backwater of the Cimarron arm of the reservoir. The water was shallow (0.5-4.5 m) with high turbidity, high flow rate, high conductivity, and rapid temperature change relative to the other sampling areas. The area served as a control in determining changes in water quality as water moved through the reservoir. Station II was about 32 km above the dam, varied in depth from 8 to 10 m, was

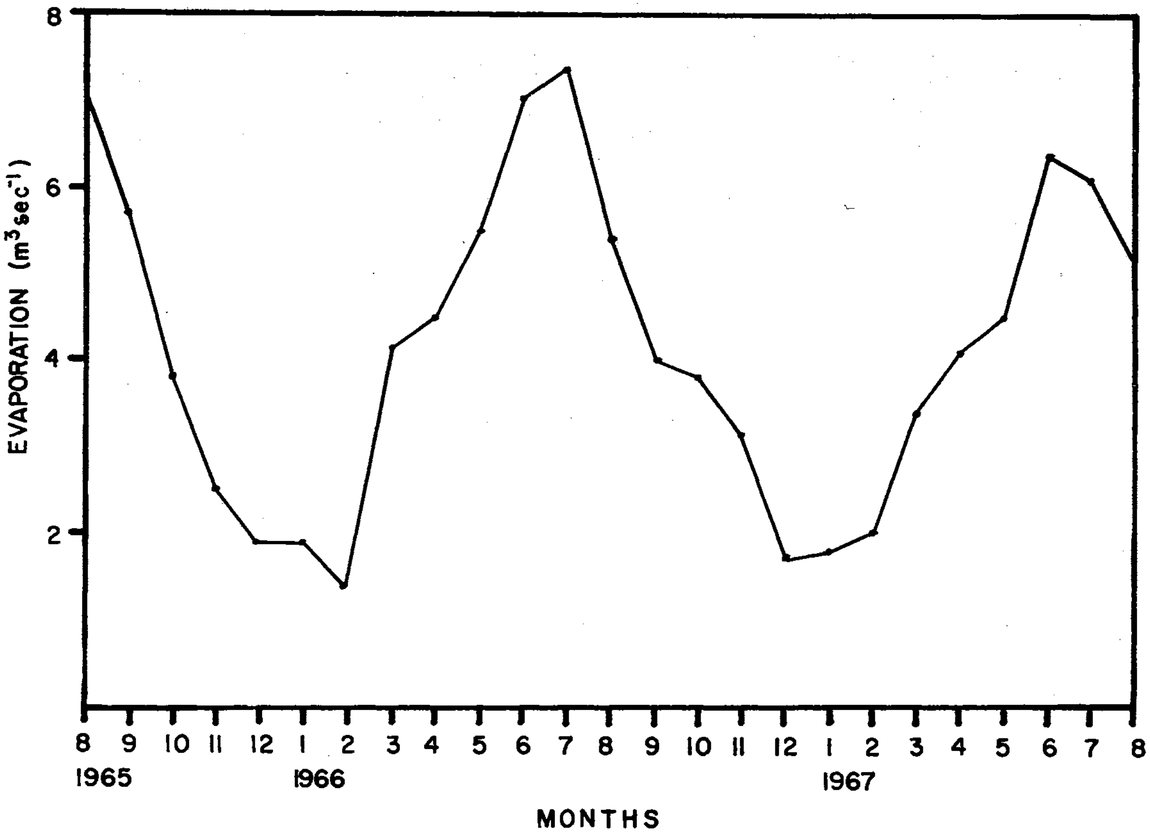

Figure 5. Temporal variations in the monthly average rate of evaporation for Keystone Reservoir derived from records of the U. S. Army Corps of Engineers

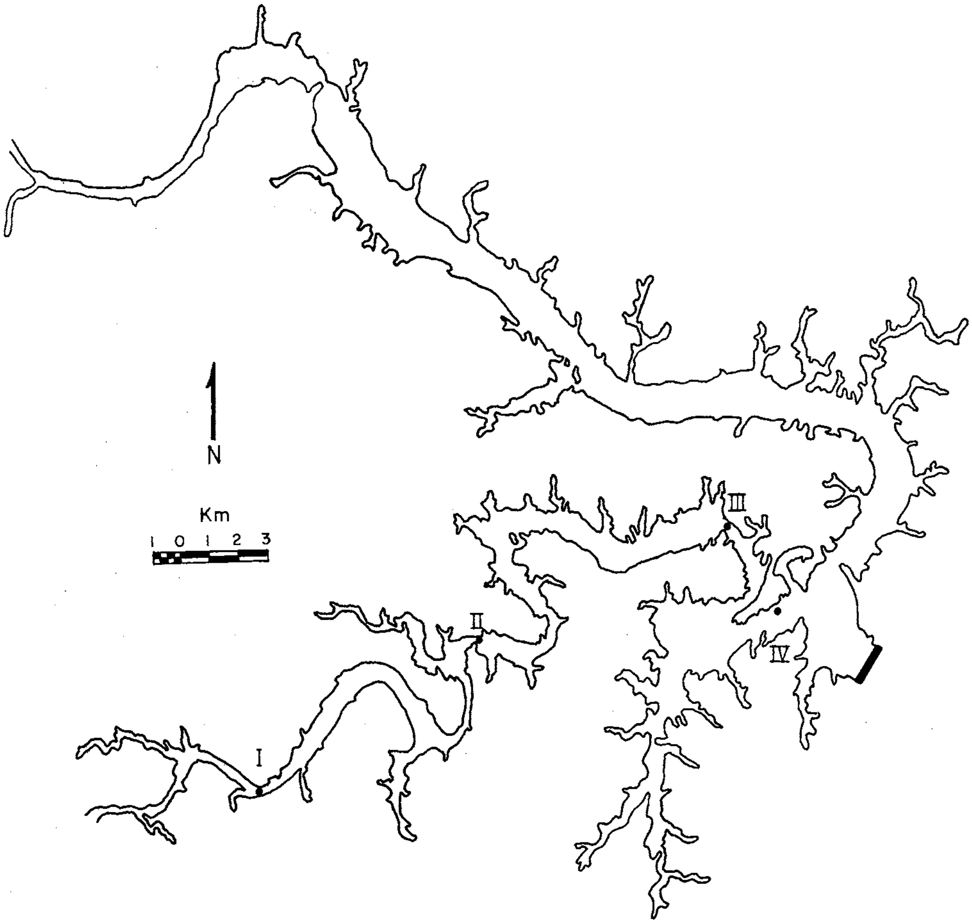

Figure 6. Keystone Reservoir, Oklahoma. Roman numerals indicate locations of sampling stations

turbid much of the year, and had reduced flow rate. Station III was located about 16 km above the dam in a constricted region where the channel makes a sharp bend. The water varied in depth from 13 to 15 m, was generally less turbid than upstream stations, and stratification was better developed than at Station II. Two large backwater areas were located between Stations II and III, and large backwaters also were located between Stations III and IV. Station IV was located 4.6 km above the dam and about 1 km above the confluence of the Cimarron and Arkansas arms. The depth of water varied from 17 to 20 m. Turbidity was usually lower than at other stations, and stratification was most pronounced.

CHAPTER III

MATERIALS AND METHODS

Sampling Procedures

Temperature, conductivity, pH, alkalinity, carbon dioxide, turbidity, dissolved oxygen, and light penetration were determined monthly at each meter of depth at four stations along the Cimarron arm during the water year 1965-66. Measurements were made of conductivity and sulfate and chloride concentrations at several points along the Cimarron and Arkansas arms and below Keystone dam in September 1965 and January, March, and May 1966.

The sampling program was expanded during 1966-67. Temperature and conductivity were measured at each meter of depth and water samples for chlorophyll and biomass determinations were collected at 3- to 5-m intervals of depth at four stations in the Cimarron arm at 1- to 2-week intervals. Measurements of turbidity, pH, alkalinity, carbon dioxide, phosphorus, ammonia and nitrate nitrogen, chloride ion, chemical oxygen demand, biochemical oxygen demand, and dissolved and suspended solids were made at each 5 m of depth at each station in the Cimarron arm at 6-week intervals from August 1966 to June 1967 and at 2-week intervals from June 1967 to September 1967. Depth profiles of temperature, oxygen, and conductivity were taken at the dam and at several locations in the Arkansas arm in November 1966 and in March 1967. Occasional estimates of the speed and direction of surface and sub-surface currents and measurements of wind velocity were made at several locations along the Cimarron and Arkansas arms.

Estimates of community metabolism were made 12-24 hr before physicochemical data were taken. Three substations were established in each of the four sampling areas to provide an estimate of variation of metabolic rates within an area. Substations were established by placing permanent buoys 200-400 m apart in the form of a triangle in water of uniform depth within each sampling area.

Water samples for laboratory analysis were collected with a Kemmerer bottle, transferred into amber polyethylene bottles, and stored on ice for transportation to the laboratory. Since ammonia is volatile in alkaline water, water samples for ammonia analyses were collected in glass bottles and fixed in the field by adding two drops of concentrated H_2SO_4 to form ammonium ion from the more volatile ammonia.

Field Measurements

Water temperature was measured using a Yellow Springs telethermometer. Micromhos of specific conductance at 25 C were measured _in situ_ using an Industrial Instruments RB solu-bridge.

Depth of light penetration was determined with a Gem submarine photometer calibrated against a pyroheliometer located on the campus of Oklahoma State University. Microamp readings taken with the photometer were converted to langleys (g cal cm^{-2} min^{-1}) by an equation, $y = 0.04136 + 0.00012x$, describing the least squares regression line fitted through calibration data (Fig. 7). Daily solar radiation was obtained from pyroheliometer readings taken by the Department of

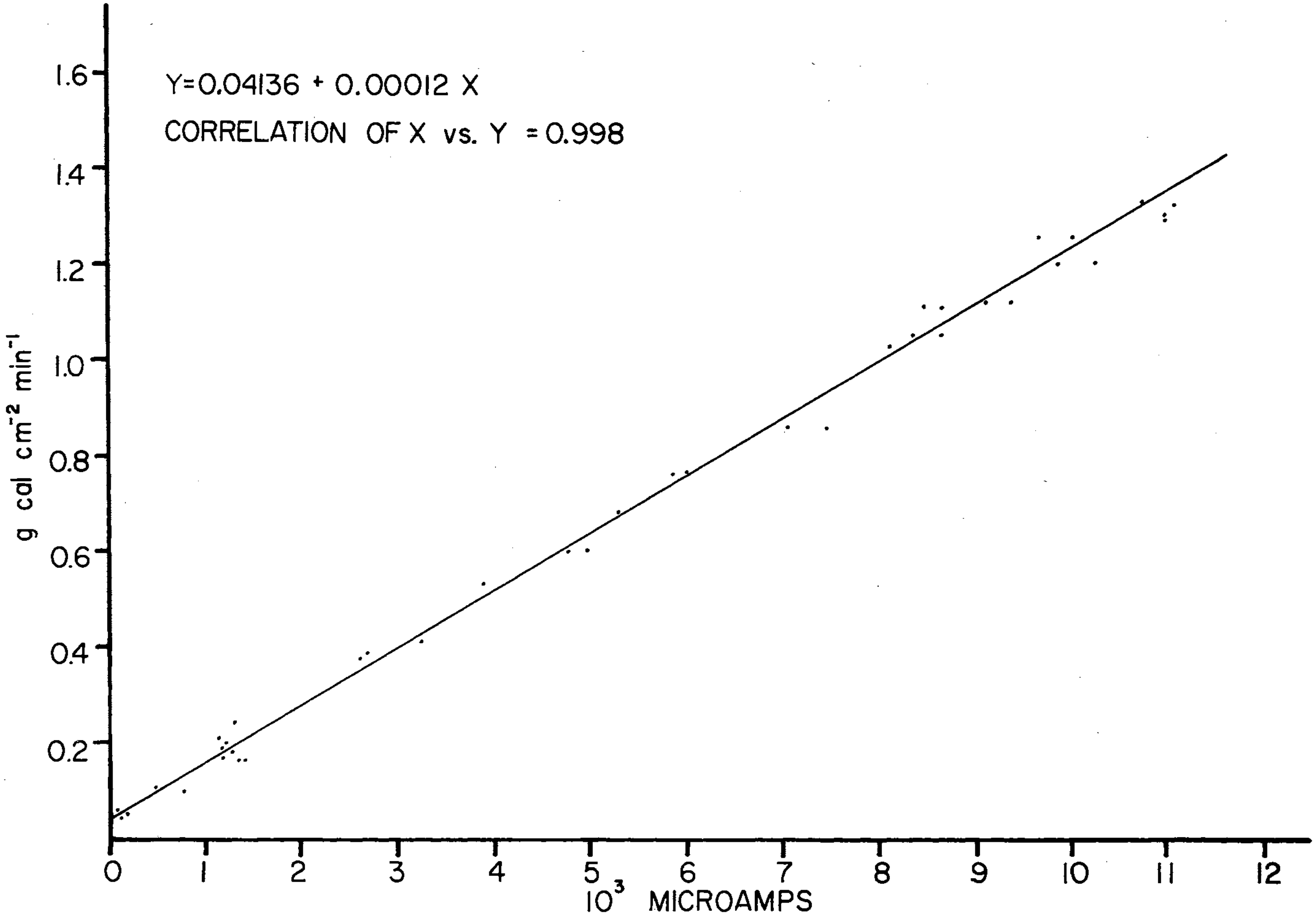

Figure 7. Regression line used to convert photometer readings (μamps) to standard langleys (g cal cm^{-2} min^{-1}) as measured by a pyroheliometer

Geography at Oklahoma State University. On days when data were missing, solar radiation values were obtained from U. S. Weather Bureau Records for Oklahoma City.

During 1965-66, dissolved oxygen samples were collected in 126 ml glass bottles, fixed in the field by the Alsterberg-azide modification of the Winkler method (A.P.H.A. 1960), and titrated in the lab with 0.01575 N sodium thiosulfate. During 1966-67, dissolved oxygen concentrations were determined <u>in situ</u> using a Precision Scientific galvanic cell oxygen analyzer equipped with a 30.5 m lead. The oxygen probe was calibrated against the Alsterberg-azide modification of the Winkler method in the laboratory before and after each field trip and twice in the field at each of the four sampling stations. Sensitivity of the oxygen probe at the temperature of the calibration sample was calculated by the formula:

$$\phi = \frac{\mu\text{amps}}{\text{g } O_3 \text{ m}^{-3}}$$

Dissolved oxygen concentrations in the reservoir were calculated from probe readings taken at each meter of depth using the equations:

$$\text{g } O_2 \text{ m}^{-3} = \frac{\mu\text{amps of unknown sample}}{\phi_1}$$

$$\text{Log } \phi_1 = \text{Log } \phi_0 + 2147.199 \left(\frac{1}{T_0} - \frac{1}{T_1} \right)$$ [1]

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[1] Personal communication from H. M. Elkhatib, Technical Service Dept., Precision Scientific Company, Chicago, Illinois.

where ϕ_1 = sensitivity of the oxygen probe at the absolute temperature of the unknown water sample,

ϕ_0 = sensitivity of the oxygen probe at the absolute temperature of the calibration sample,

T_1 = absolute temperature of unknown sample (K),

T_0 = absolute temperature of the calibration sample (K).

Hydrogen ion concentration was measured by use of a Hellige Comparator. Phenolpthalein and methyl purple alkalinity were determined by field titration with 0.02 N sulfuric acid (A.P.H.A. 1960). Stoichiometric classification of carbonate and bicarbonate alkalinities is expressed as g $CaCO_3$ m^{-3}. Free carbon dioxide was estimated from a nomograph using pH and bicarbonate alkalinity (Moore 1939).

Laboratory Techniques

Special techniques of cleaning and storing sample bottles and laboratory glassware between each set of analyses were necessary to prevent contaminations in sensitive colorimetric analyses. Sample bottles and all glassware were washed with a strong commercial wetting agent, rinsed three times with distilled water, rinsed with hot 30% sulfuric acid, and finally rinsed four to six times with double, glass-distilled, deionized water. Glassware was allowed to drain dry, and openings were covered with aluminum foil for storage. Water which had been distilled in a Barnstead water still and re-distilled in an all-glass still was further deionized by passage through a glass column 10 cm in diameter and 1.2 m long filled with research grade, mixed-bed, ion-exchange resin.

In the laboratory, water samples were kept in a cold room at 2 C until analyses were completed. Analytical procedures usually were started on all samples within 6 hr after collection, and all analyses normally were completed within 24 hr after sample collection.

Samples which required separation into soluble and particulate fractions for chemical analysis were filtered immediately after returning to the laboratory by passing water through 0.22 μ Millipore filters. Water samples used in determination of chlorophyll a and biomass were concentrated by centrifugation at the rate of 1 liter per 7 min with a Foerst plankton centrifuge.

Absorbances of solutions in colorimetric analyses were read on a Beckman DB-G recording spectrophotometer. Automatic slit width program for medium width was used. Most samples were read in 4 cm quartz cells, but 1 cm cells were used for samples having extremely high concentrations. Distilled water was used in the reference cells. The wave length at which absorbance was measured was selected from scans of standards of several known concentrations. The selected wave length was a compromise of resolution, least slope of the tangent to the curve, and adherence to Beer's Law.

Laboratory Analyses

Phosphorus

One-half of each sample for phosphorus analyses was filtered through 5 μ and 0.22 μ Millipore filters. Rigler (1964) found that 0.22 μ Millipore filters removed 95% of the particulate organic phosphorus, while the commonly used 0.45 μ Millipore filters removed only 76% of the particulate organic phosphorus in seston of an Ontario lake.

Samples of both filtered and unfiltered water were digested by persulfate oxidation (Menzel and Corwin 1965) for 1 hr in a boiling water bath. Phosphorus was determined in the filtered and unfiltered digested samples and in a filtered undigested sample by the single solution method of Murphy and Riley (1962). Absorbance was read at 720 mμ after 15 min color development. The advantages of the colorimetric method of Murphy and Riley over the standard stannous chloride method (A.P.H.A. 1960) are that antimony is used to promote rapid color development so there is less chance of interference by dissolved organic phosphorus compounds with inorganic phosphate analyses; the molybdenum blue color is more stable; and errors due to chloride interference are less than 1%.

Standard curves were prepared by using standard solutions of potassium dihydrogen phosphate at concentrations from 0.050 to 2.000 g P m^{-3} (Fig. 8). Undigested standards followed Beer's Law throughout the range of concentrations tested, and absorbances of unknown samples were converted to concentrations by equations representing least squares regression lines fitted through plots of absorbance versus concentration of standards. Plots of digested standards formed smooth curves with slopes that decreased with higher concentrations (Fig. 8). Since the only difference between the two procedures was digestion with potassium persulfate, apparently the digestion procedure caused a decrease in color proportional to concentration. Absorbances of digested phosphorus samples were converted graphically from the standard curve, since considerable error would occur at concentrations above 1.0 g P m^{-3} if a straight line was fitted to the data and the resulting equation used to convert absorbance to concentration.

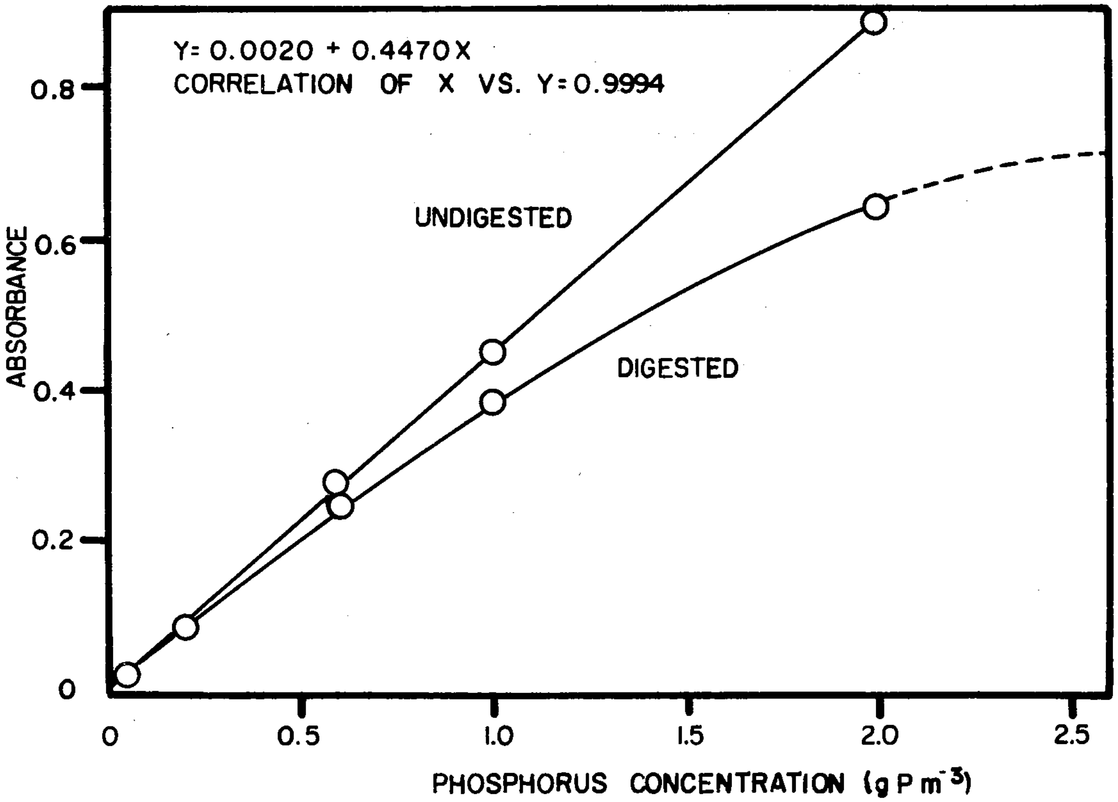

Figure 8. Regression line of undigested phosphorus standards and curve of digested phosphorus standards. Each point represents the mean of six replicates.

The various forms of phosphorus occurring in the reservoir water were calculated from the unfiltered digested, filtered digested, and filtered undigested determinations in the following manner:

A = Unfiltered, digested
B = Filtered, digested
C = Filtered, undigested

Total phosphorus = A
Total dissolved phosphorus (inorganic and organic) = B
Dissolved inorganic phosphorus = C
Total organic phosphorus (D) = A-C
Dissolved organic phosphorus (E) = B-C
Particulate organic phosphorus = D-E

To check the accuracy of the method in determining phosphorus concentrations of unknown samples, absorbances of standards used to obtain the standard curve shown in Fig. 7 were converted to concentrations by means of the linear regression equation, $x \text{ (g P m}^{-3}\text{)} = \frac{y\text{(absorbance)} - 0.00198}{0.44704}$ (Table IV). Comparison of the calculated concentration with the actual concentration of standards gives an indication of the error incurred in using the regression equation for determining unknown concentrations.

Since replicate water samples were not taken for phosphorus analyses during the normal sampling procedure, an experiment was conducted at Station III in August 1967 to provide an estimate of the precision of the phosphorus method and to give an indication of the variation in phosphorus concentrations among substations within a sampling area (Table V). Duplicate samples were collected from 1 m and 14 m at each

TABLE IV

CONVERSION OF ABSORBANCES OF PHOSPHORUS STANDARDS TO CONCENTRATION BY USE OF THE STANDARD REGRESSION EQUATION*

Actual Concentration (g P m^{-3})	Absorbance at 720 mμ	Concentration Calculated From Regression Equation (g P m^{-3})	Error (g P m^{-3})
0.050	0.021	0.043	-0.007
	0.023	0.047	-0.003
0.200	0.088	0.192	-0.008
	0.094	0.206	+0.006
0.600	0.265	0.588	-0.012
	0.281	0.624	+0.024
1.000	0.440	0.984	-0.016
	0.463	1.036	+0.036
2.000	0.874	1.955	-0.045
	0.914	2.046	+0.046

*Absorbance values are the minimum and maximum of each set of six replicate standards used to obtain data in Figure 8.

TABLE V

PRECISION OF PHOSPHORUS ANALYSES AND VARIATION IN PHOSPHORUS CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g P m^{-3})

	Sub-station	Total	Dissolved Inorganic	Total Organic	Dissolved Organic	Particulate Organic
			Replicates from 1 m			
	1	0.627	0.239	0.388	0.031	0.357
		0.632	0.239	0.393	0.039	0.354
	2	0.606	0.242	0.364	0.038	0.326
		0.598	0.246	0.352	0.034	0.318
	3	0.649	0.244	0.405	0.032	0.373
		0.606	0.246	0.360	0.034	0.326
Mean		0.620	0.243	0.377	0.035	0.342
Standard Deviation		± 0.017	± 0.003	± 0.021	± 0.003	± 0.022
			Replicates from 14 m			
	1	0.677	0.246	0.431	0.039	0.392
		0.680	0.253	0.427	0.027	0.400
	2	0.680	0.250	0.430	0.032	0.398
		0.668	0.253	0.410	0.029	0.381
	3	0.680	0.246	0.434	0.030	0.404
		0.650	0.244	0.406	0.028	0.378
Mean		0.672	0.249	0.423	0.031	0.392
Standard Deviation		± 0.012	± 0.004	± 0.012	± 0.004	± 0.012

of the three substations at Station III. There was no significant difference ($\alpha = 0.05$) in concentration of phosphorus among substations within the sampling area. Precision of the phosphorus method of analysis was good, even though the total phosphorus concentration was less than 1 g P m^{-3}. Coefficients of variation of the analytical procedures used to estimate various forms of phosphorus were 2.2% for total phosphorus, 1.4% for inorganic phosphorus, and 6.6% for organic phosphorus. The larger coefficient of variation for organic phosphorus was expected since it is calculated from the difference between two separate determinations.

Ammonia Nitrogen

The direct nesslerization method was used for ammonia nitrogen determinations (A.P.H.A. 1960). Interference from calcium, magnesium, iron, and sulfide was eliminated by making samples alkaline and removing the resulting precipitate by filtration. A number of aliphatic and aromatic amines, organic chloramines, alcohols, aldehydes, and acetone interfere with the method by causing turbidity with nessler reagent. No correction was made for interferences from these compounds. Color intensity was determined photometrically at 425 mμ after allowing 10 min for color development. Ammonium chloride was used to prepare ammonia standard curves. Absorbance of standards from 0.200 to 2.000 g N m^{-3} adhered to Beer's Law (Fig. 9). To obtain an estimate of the error involved in determining concentrations of unknown samples by use of the regression equation obtained from data in Fig. 9, the concentration of each standard was calculated from its absorbance using the regression equation and compared with the actual concentration (Table VI).

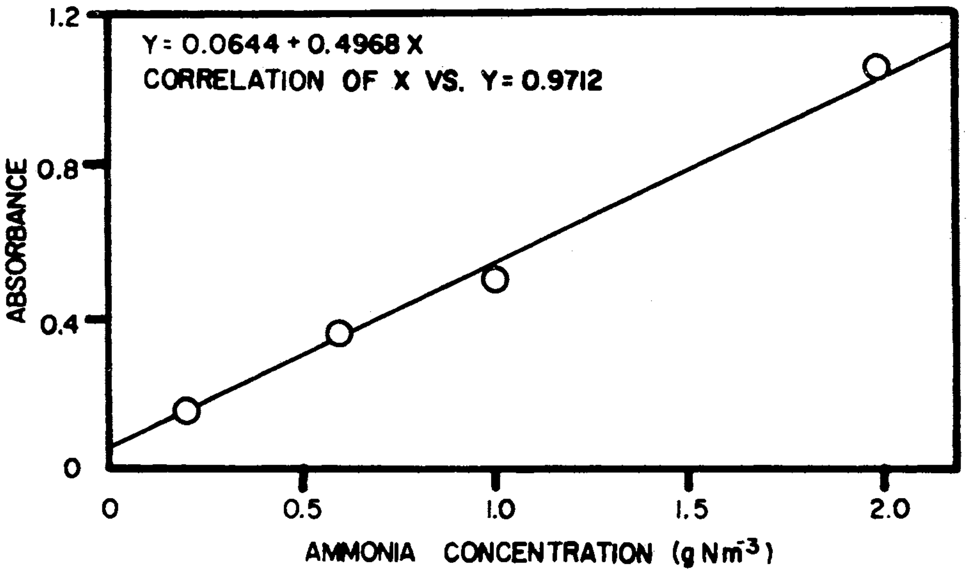

Figure 9. Regression line of ammonium chloride standards. Each point represents the mean of six replicates.

TABLE VI

CONVERSION OF ABSORBANCE OF AMMONIUM CHLORIDE STANDARDS TO CONCENTRATION BY USE OF THE STANDARD REGRESSION EQUATION*

Actual Concentration (g N m^{-3})	Absorbance at 425 mμ	Concentration Calculated From Regression Equation (g N m^{-3})	Error (g N m^{-3})
0.200	0.246	0.041	-0.159
	0.417	0.386	+0.186
0.600	0.490	0.533	-0.067
	0.592	0.738	+0.138
1.000	0.651	0.857	-0.143
	0.763	1.082	+0.082
2.000	1.100	1.761	-0.239
	1.400	2.364	+0.364

*Absorbance values are the minimum and maximum of each set of six replicate standards used to obtain data in Figure 9.

Ammonia was absent or below the minimum detectable concentration on dates when experiments to estimate variation in ammonia concentrations among substations within a sampling area were attempted. A.P.H.A. (1960) reported a standard deviation of ± 0.09 g N m^{-3} obtained with an "unknown" sample of river water which contained 0.40 g N m^{-3} in 17 laboratories using the direct nesslerization method.

Nitrate Nitrogen

Nitrate nitrogen was determined using the reagents and procedures of the Hach Chemical Company. Absorbance was read at 415 mμ after 10 min color development. Standard curves for nitrate analyses were prepared with potassium nitrate standards ranging in concentration from 0.05 to 2.00 g N m^{-3}. Absorbance of standards adhered to Beer's Law throughout the concentration range (Fig. 10).

To estimate the precision of nitrate analyses and variation in nitrate concentration among substations within a sampling area, duplicate samples were collected at each of the three substations at 1 and 14 m of depth at Station III in August 1967. An analyses of variance showed no significant differences ($\alpha = 0.05$) among substations and gave an average coefficient of variation for the method of 48% (Table VII).

Chloride and Sulfate Ions

Chloride ion was measured by the standard Mohr method using potassium chromate as the indicator and 0.0141 N silver nitrate as the titrant (A.P.H.A. 1960). Sulfate was determined by a standard gravimetric method with ignition of residue at 800 C after precipitation of sulfate in a hydrochloric acid medium as barium sulfate by the addition of barium chloride (A.P.H.A. 1960).

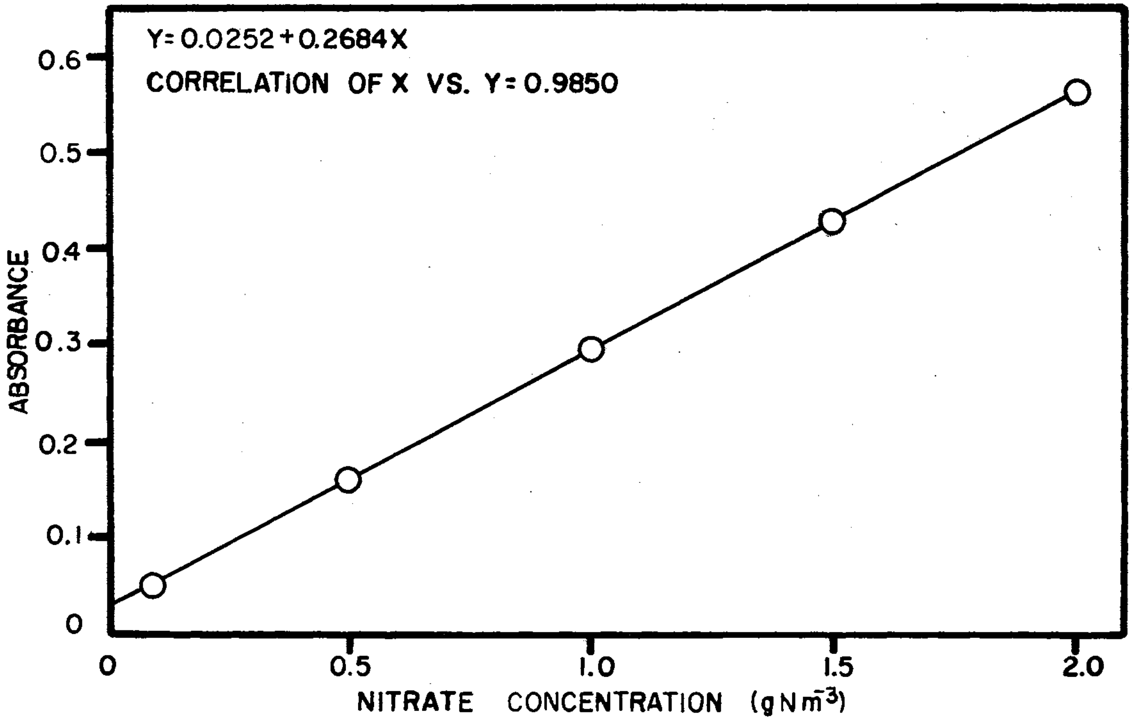

Figure 10. Regression line of potassium nitrate standards. Each point represents the mean of six replicates.

TABLE VII

PRECISION OF NITRATE ANALYSES AND VARIATION IN NITRATE CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g N m^{-3})

Depth in m	Substations			$\bar{x} \pm s$
	1	2	3	
1	0.189 0.059	0.081 0.111	0.077 0.115	0.105 ± 0.045
14	0.022 0.126	0.070 0.193	0.137 0.167	0.119 ± 0.063

To estimate the precision of chloride analyses and variation in chloride concentration among substations within a sampling area, duplicate samples were collected at each of the three substations at 1 and 14 m of depth at Station III in August 1967. An analyses of variance showed no significant differences ($\alpha = 0.05$) among substations and gave an average coefficient of variation for the method of 1.9% (Table VIII). A.P.H.A. (1960) reported that 23 laboratories obtained a standard deviation of ± 6 g Cl m^{-3} for a synthetic sample containing 219 g Cl m^{-3}. The precision of the sulfate procedure was not determined in our laboratory, but A.P.H.A. (1960) reported a standard deviation of ± 9 g SO_4 m^{-3} obtained by 21 laboratories using a sample containing 288 g SO_4 m^{-3}.

TABLE VIII

PRECISION OF CHLORIDE ANALYSES AND VARIATION IN CHLORIDE CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g Cl m^{-3})

Depth in m	Substations 1	2	3	$\bar{X} \pm S$
1	370	360	350	
	360	360	360	358 ± 8
14	360	360	360	
	370	350	360	366 ± 6

Chemical Oxygen Demand

Chemical oxygen demand (COD) was estimated by refluxing water samples with 0.025 N potassium dichromate and back titrating the unreduced dichromate with 0.025 N ferrous ammonium sulfate using ferrion indicator (A.P.H.A. 1960). The principal inadequacies of this method are that straight-chain aliphatic compounds and aromatic hydrocarbons are not oxidized to any appreciable extent, and chlorides are quantitatively oxidized by this procedure in the presence of organic matter. More complete oxidation can be obtained by adding silver sulfate as a catalyst. A correction for chlorides can be calculated by multiplying 0.226 times the chloride concentration, since 1 g Cl^- m^{-3} = 0.226 g O m^{-3}. However, if silver sulfate is used as a catalyst to facilitate the oxidation of straight-chain alcohols and acids, chloride precipitates some of the silver ion and thereby decreases the catalytic efficiency and invalidates the chloride correction factor.

Dobbs and Williams (1963) have reported a procedure whereby chlorides are complexed with mercuric ion and eliminated from interfering with the oxidation reaction. They reported that a ratio of mercuric to chloride ion of 5:1 completely inhibited chloride oxidation in samples of distilled water containing 100-2000 g Cl^- m^{-3}. Their results indicated that a 4:1 ratio was sufficient to prevent chloride oxidation in a pure system, but since mercuric ion is known to form complexes with certain other ions found in natural waters, a higher ratio was preferable. An attempt to duplicate the results of Dobbs and Williams (1963) was made in our laboratory. The COD of several 25 ml samples containing from 200 to 1600 g Cl^- m^{-3} was determined by the procedure of Dobbs and Williams (1963). Sufficient mercuric sulfate (0.5 g $HgSO_4$) was added to the 25 ml samples to provide a mercuric to chloride ion ratio of 5:1 for 2700 g Cl^- m^{-3}. In our experiment mercuric sulfate eliminated chloride interference up to 600 g Cl^- m^{-3}, but at higher concentrations error due to oxidation of chlorides was significant (Fig. 11). Since the concentration of chlorides in the hypolimnion of Keystone Reservoir usually is greater than 600 g Cl^- m^{-3}, this method was not considered satisfactory.

The procedure chosen for use on water from Keystone Reservoir was to reflux the mixture without catalyst for 20 min to oxidize all chlorides, allow the mixture to cool, and then add silver sulfate catalyst (A.P.H.A. 1960). By following this procedure complete catalytic action was obtained, and a correction for chloride interference could be applied. To check the validity of using the theoretical relationship

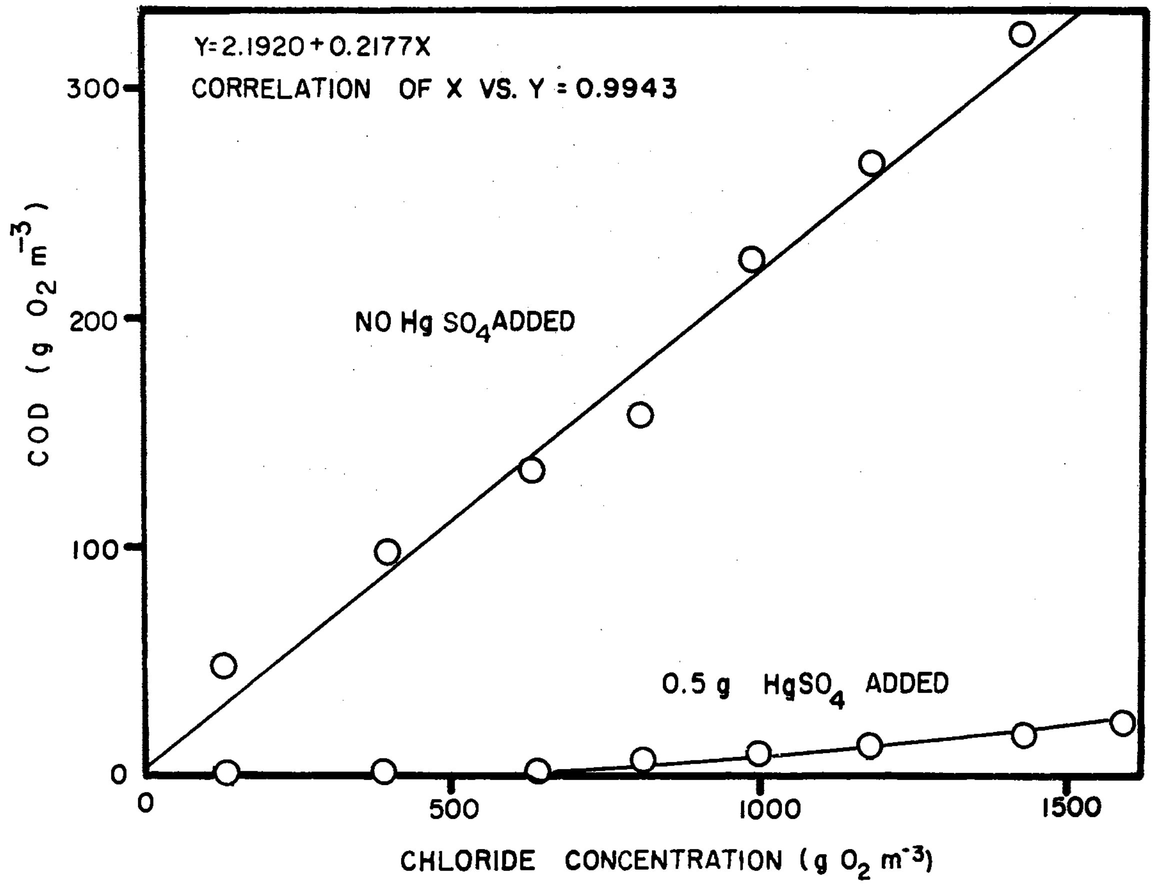

Figure 11. Curve and regression line of chemical oxygen demand of chloride standards with and without the addition of mercuric sulfate.

between chloride ion and oxygen (1 g $Cl^- m^{-3}$ = 0.226 g 0 m^{-3}) to correct for chloride interference, the COD of several distilled water-chloride standards was determined using the standard procedure (Fig. 11). The regression line fitted through a plot of COD versus chloride concentration had a slope of 0.218 with a correlation of COD versus Cl^- concentration of 0.994. Student's t-test (α = 0.05) failed to show a significant difference between the experimental slope of 0.218 and the theoretical slope of 0.226; therefore, the theoretical relationship was assumed to be valid and was used in making chloride corrections.

The precision of the COD method and variation in COD concentrations among substations within a sampling area were estimated from duplicate samples collected from 1 and 14 m of depth at three substations at Station III in August 1967. An analysis of variance gave an average standard deviation of ± 9.5 g 0_2 m^{-3} and a coefficient of variation of 67% (Table IX). No differences (α = 0.05) among substations within a sampling area could be demonstrated. The precision of the method was not sufficient to detect small differences among areas with low COD concentrations. The method was useful for estimating the order of magnitude of the COD of reservoir water and for detecting influxes of highly polluted water. The Analytical Reference Service found the precision of the standard COD method to be ± 24.6 g 0_2 m^{-3} with the mean analytical value 92% of the theoretical COD using a prepared mixture of glucose and glutamic acid with a theoretical COD of 308 g 0_2 m^{-3} (Ballinger and Lishka 1962).

TABLE IX

CHEMICAL OXYGEN DEMAND DATA SHOWING THE CHLORIDE CORRECTION, PRECISION OF ANALYSES, AND VARIATION IN COD CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

Depth	Sub-station	$g\ Cl^-\ m^{-3}$	Uncorrected COD $g\ O_2\ m^{-3}$	Cl correction $g\ O_2\ m^{-3}$	Corrected COD $g\ O_2\ m^{-3}$
1 m below surface	1	370	129	83	46
		360	114	81	33
	2	360	99	81	18
		360	99	81	18
	3	350	106	78	28
		350	99	78	21
				$\bar{X} \pm S$ =	27.3 ± 10.9
14 m below surface	1	360	91	81	10
		370	68	83	0
	2	360	99	81	18
		350	84	78	6
	3	360	68	81	0
		360	99	81	18
				$\bar{X} \pm S$ =	8.7 ± 8.2

Biochemical Oxygen Demand

Five-day and 20-day biochemical oxygen demands were determined by standard methods (A.P.H.A. 1960), modified for use on low-BOD, reservoir water. One ml each of phosphate buffer, magnesium sulfate, calcium chloride, and ferric chloride solutions and 5 ml of settled sewage from the primary settling tank of the Stillwater sewage treatment plant were added to 1 liter of reservoir water. The sample was saturated with dissolved oxygen by shaking in a flask, and three 250 ml BOD bottles were filled. Duplicate distilled water blanks were prepared by using 1 liter of distilled water as sample water. Samples were placed in an ice chest to retard biochemical activity during transportation to the laboratory. In the laboratory the dissolved oxygen in one of the triplicate bottles was determined by the Alsterberg-azide modification of the Winkler method (A.P.H.A. 1960). The remaining two bottles were incubated in a water bath at 20 C. The concentration of dissolved oxygen in the second bottle was determined 5 days after the initial determination, and the dissolved oxygen concentration in the third bottle was determined 20 days after the initial determination. By subtracting the 5- and 20-day determinations from the initial determination, the biochemical oxygen demand was calculated. By subtracting the distilled water blank from the total oxygen demand, the oxygen demand of the sewage seed was eliminated, and the true BOD of the sample of reservoir water was known.

On several occasions a more extensive series of determinations were made in which the BOD of reservoir water was determined after 1, 3, 5, 7, 9, 11, 13, 15, 17, and 20 days of incubation. By plotting oxygen uptake versus incubation time, it was determined that the total

BOD of reservoir water was exerted before the 20th day of incubation (Fig. 12). Therefore, it was valid to assume that the 20-day BOD represented the ultimate BOD of the water for the purpose of calculating the first-order reaction constant k (personal communication from D. F. Kincannon, OSU). The reaction constant k was calculated by the equation, $k = \frac{\log L - \log (L-Y)}{t}$, derived from the theoretical relationship determined by Theriault (1927):

$$Y = L\,(1 - 10^{-kt})$$

where Y = 5-day BOD,

L = ultimate BOD (20-day BOD),

t = incubation time required for the exertion of Y (which in this case equals 5 days), and

k = first order reaction constant in day^{-1} units.

To provide an estimate of the precision of 5-day BOD analyses and of variation in 5-day BOD concentration among substations within a sampling area, duplicate samples were collected at the three substations at 1 and 14 m of depth at Station III in August 1967. An analysis of variance indicated no significant differences ($\alpha = 0.05$) among substations and gave a coefficient of variation for the method of 54% (Table X).

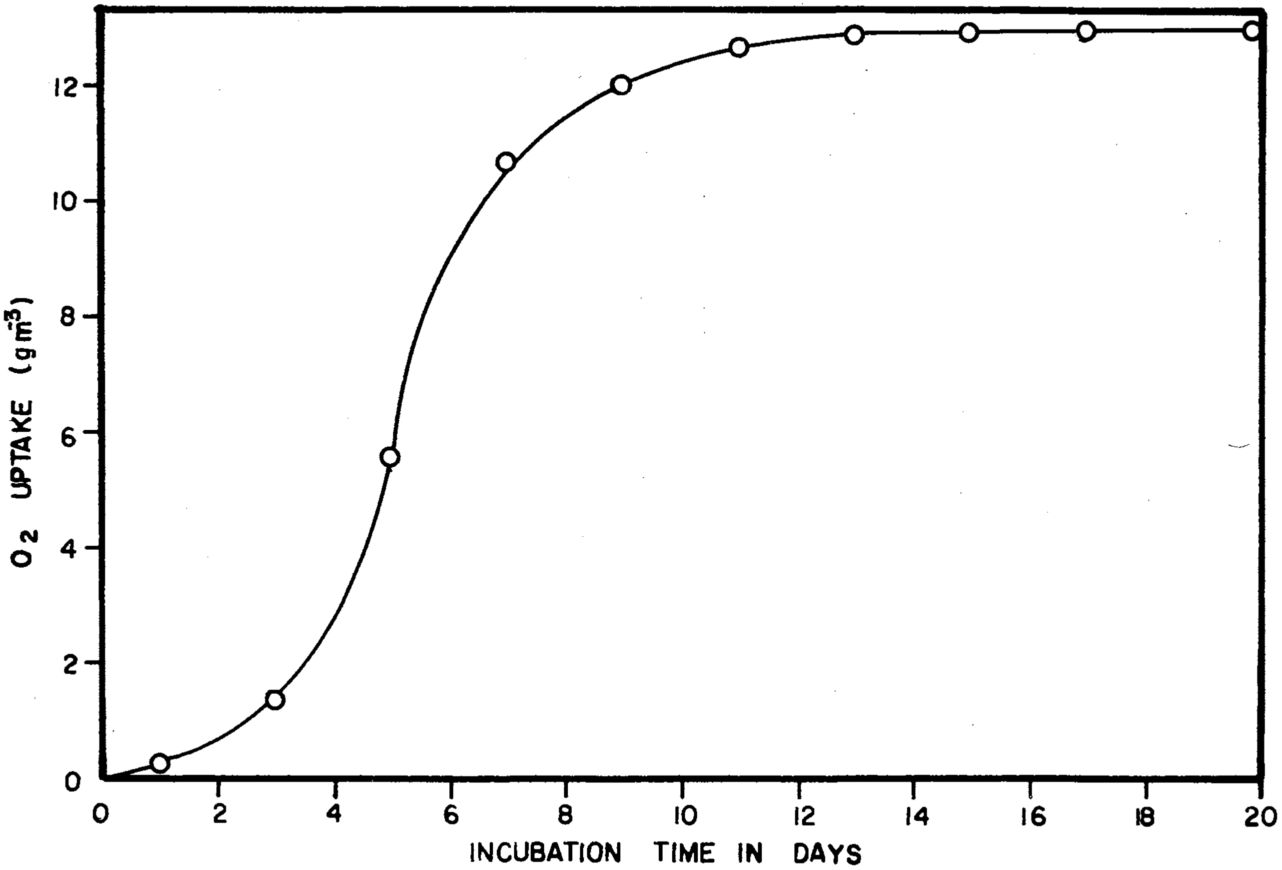

Figure 12. BOD exerted over time by water from Keystone Reservoir, January 1966

TABLE X

PRECISION OF 5-DAY BOD ANALYSES AND VARIATION IN 5-DAY BOD CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g O_2 m^{-3} day^{-1})

Depth in m	Substations 1	2	3	$\bar{x} \pm s$
1	1.9	0.5	0.5	
	1.9	1.6	1.0	1.2 ± 0.7
14	0.6	1.1	2.1	
	0.5	1.8	1.0	1.2 ± 0.6

Solids

Standard gravimetric procedures were used to analyze for dissolved, suspended, and total solids, and an attempt was made to differentiate between organic and inorganic solids. Water samples for gravimetric analysis were divided into filtered and unfiltered portions by filtration through 0.22 μ Millipore filters. A 50 ml sample of filtered and a 50 ml sample of unfiltered water each were placed in tared porcelain crucibles and dried at 105 C for 24 hr. Crucibles were cooled to room temperature in a desiccator and weighed to the nearest 0.0001 g on a Mettler balance. Crucibles then were ignited in a muffle furnace at 600 C for 1 hr. After ignition, crucibles were placed in an oven, and 50 ml of distilled water, which had been saturated with carbon dioxide, were pipetted into each crucible. This procedure was followed because calcium carbonate is broken down upon ignition, liberating carbon dioxide as a gas. Loss of inorganic elements would result in a positive error in the determination of organic solids. By adding carbon dioxide water, the carbonate balance was restored according to the following equations:

(Loss) $CaCO_3 \longrightarrow CaO + CO_2\uparrow$

(Restoration) $H_2O + CO_2 \longrightarrow H_2CO_3$

$CaO + 2H_2CO_3 \longrightarrow CaCO_3 + 2H_2O\uparrow + CO_2\uparrow$

Crucibles were dried at 105 C for 24 hr, cooled in desiccators, and weighed on a Mettler balance. Distilled water blanks and empty crucibles were run as controls. Weight of residue of the distilled water blanks was subtracted from the loss of weight on evaporation to correct for any solids contained in carbon dioxide-saturated water added after ignition. Using the tared, evaporated, and ignited weights, the following calculations were made:

Loss on evaporation (g) = evaporated weight - tared weight

Loss on ignition (g) = evaporated weight - ignited weight

Definitions: E = loss on evaporation (g)
I = loss on ignition (g)
U = unfiltered
F = filtered

a. total solids (g m^{-3}) = UE x 20,000
b. total organic solids (g m^{-3}) = UI x 20,000
c. total inorganic solids (g m^{-3}) = a-b
d. total dissolved solids (g m^{-3}) = FE x 20,000
e. dissolved organic solids (g m^{-3}) = FI x 20,000
f. dissolved inorganic solids (g m^{-3}) = d-e
g. total suspended solids (g m^{-3}) = a-d
h. suspended organic solids (g m^{-3}) = b-e
i. suspended inorganic solids (g m^{-3}) = (c-f) or (g-h)

Theoretically, all of these parameters can be calculated from this analysis, but it was found that error in the method using relatively heavy crucibles and small water samples was too great for estimation of all parameters except dissolved, suspended, and total solids. A net analytical error of 0.0002 g caused an error of 8 g m^{-3} in final calculations. Consequently, since most of these parameters were not of greater magnitude than 5-20 g m^{-3} in Keystone Reservoir, they could not be determined accurately.

An analysis of variance of duplicate samples collected from each of the three substations at 1 and 14 m of depth at Station III in August 1967 gave standard deviations ranging from ± 6 to ± 24 g m^{-3}, while means ranged from 18 to 854 g m^{-3} (Table XI). The rather constant deviations despite the large range in magnitude of the means yielded average coefficients of variation of 2.4% for total solids, 1.0% for dissolved solids, and 55.3% for suspended solids. The consistency of standard deviations regardless of the concentration of solids indicated that estimating the fourth decimal place during weighing was the major source of variation in these analyses.

Turbidity

Turbidity, as measured with a Bausch and Lomb Spectronic 20 colorimeter calibrated against a Jackson Turbidimeter, is expressed as "Turbidity Units," roughly equivalent to g suspended solids m^{-3}.

Biomass

Ash-free weight (loss on ignition) determinations were used to estimate biomass. Samples were prepared by centrifuging 100 to 500 ml of reservoir water and diluting with distilled water and commercial formalin to a final volume of 10 ml. Samples were placed in porcelain crucibles, dried 24 hr at 105 C, weighed on a Mettler balance, ignited

TABLE XI

PRECISION OF GRAVIMETRIC ANALYSES AND VARIATION IN CONCENTRATIONS OF SOLIDS AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g m^{-3})

Depth in m	Sub-station	Total Solids	Dissolved Solids	Suspended Solids
1m	1	868	838	30
		858	834	24
	2	838	828	10
		836	826	10
	3	828	820	8
		860	830	30
	$\bar{X} \pm S$	848 ± 16	830 ± 6	18 ± 10
14m	1	840	820	20
		842	826	16
	2	838	832	6
		860	838	22
	3	900	830	20
		846	806	40
	$\bar{X} \pm S$	854 ± 24	826 ± 11	20 ± 11

for 2 hr at 550 C in a muffle furnace, and reweighed.

The Foerst centrifuge is less than 100% efficient in concentration of plankton (Hartman 1958, Laskar and Holmes 1957, Reinhard 1931). Parallel series of 48 samples, taken on two dates at all four sampling stations, were used to compare centrifugation at the rate of 1 liter per 7 min to filtration through 0.22 μ Millipore filters. Biomass amounts obtained by the filters were 38.3 ± 13.5% higher than those obtained by centrifugation. Therefore, biomass values were multiplied by 1.38. Wright (1959) found an average loss of biomass by centrifugation of 28%.

To provide an estimate of the precision of biomass analyses and of variation in biomass concentration among substations within a sampling area, duplicate samples were collected from each of the three substations at 1, 8, and 14 m of depth at Station IV in March 1968. Analyses of variation among substations within depths gave coefficients of variation of 32% at 1 m, 19% at 8 m, and 2% at 14 m (Table XII). The high coefficients of variation for samples at 1 and 8 m of depth are indicative of the patchiness of the phytoplankton population in the epilimnion. The low coefficient of variation at 14 m of depth indicated a lack of patchiness of seston in the hypolimnion. Significant differences ($\alpha = 0.05$) were found among average biomass concentrations at the three substations at 1 and 8 m of depth. Significant differences ($\alpha = 0.05$) could not be demonstrated among average biomass concentrations at the three substations at 14 m of depth.

TABLE XII

PRECISION OF BIOMASS ANALYSES AND VARIATION IN BIOMASS CONCENTRATION AMONG SUBSTATIONS WITHIN A SAMPLING AREA

(All Concentrations as g m^{-3})

Depth in m	Substations 1	2	3	$\bar{X} \pm S$
1	3.50	1.93	2.87	
	3.50	1.35	2.87	2.67 ± 0.86
8	3.01	0.66	2.37	
	3.26	0.50	1.68	1.97 ± 0.37
14	2.59	1.52	1.54	
	2.11	1.74	1.60	1.85 ± 0.04

Chlorophyll a

Chlorophyll a concentrations were determined by Spangler (1969) using the methods of Richards with Thompson (1952) and Parsons and Strickland (1963). Water samples were concentrated for chlorophyll determinations by centrifugation at the rate of 1 liter per 7 min with a Foerst plankton centrifuge and removing the remaining water from the centrifugate by filtration through 0.45 μ Millipore filters. Parallel series of samples comparing the centrifuge to the Millipore filter showed that amounts of chlorophyll a obtained by Millipore filters were higher by 21% (Spangler 1969). Therefore, results of quantitative pigment determinations were multiplied by 1.21. The average loss of chlorophyll a (21%) from the centrifuge was less than the average loss of biomass (38%). The difference between the percent loss of biomass and chlorophyll a was due to a greater relative loss of light seston than heavier phytoplankton in the water being removed by centrifugation.

Statistical Analyses

Analyses of variance and tests for differences between water years 1965-66 and 1966-67, among stations, among dates, and among depths within a station were made using the Hierarchical AOV, Factorial, and Duncan's Multiple Range computer programs of the Oklahoma State University Statistical Laboratory. Least squares regression lines were fitted through data points using the Multiple Linear Regression computer program of the Oklahoma State University Computing Center. Student's t-test, used to test for homogeneity of regression, and the chi-square test, used to test for homogeneity of variances, were made according to the procedures of Steel and Torrie (1960).

Since duplicate observations of physicochemical parameters were not made, estimates of true error terms could not be determined. In analysis of variance for these parameters a factorial arrangement of treatments was used with sampling stations composing the levels of one factor and dates composing the levels of the second factor. The date x station interaction was used as an estimate of error in making F-tests for significant differences. Throughout the second year of study, triplicate observations of temperature and dissolved oxygen concentration were made at each sampling depth at each station. The date x station interaction was present during 1966-67 for temperature and dissolved oxygen concentration. It is likely that the interaction was present for other physicochemical parameters during both years of study; therefore, interaction "error terms" used in testing for significant differences were too large. The use of excessively large error terms would result in a decrease in sensitivity of statistical tests used to detect significant differences among treatment means. However, confidence can be placed in conclusions drawn from means that were shown to be significantly different because the true probability of a significant difference actually was higher than the demonstrated probability.

Data on the rate of community metabolism at each station were analyzed separately using a randomized block design with dates as treatments and substations within stations as blocks (Table XIII). Error mean squares for gross productivity and community respiration were extremely low for Station I and high for Station IV. A chi-square test for homogeneity of variances showed the variances of Station I and IV to be significantly different ($\alpha = 0.01$) from each other and from Stations II and III, but Stations II and III were not significantly different. Pooled variances were not valid error terms since the assumption of homogeneity was not true for all stations. Therefore, a substation x date within station error term was used to test for significant differences among dates within each station using the least significant difference test (Steel and Torrie 1960). To test for significant differences among station means averaged over time, t-tests were made between means using an error term computed by the formula:

$$s^2 = \frac{s_1^2 + s_2^2}{n}$$

where s_1^2 and s_2^2 are the variances of the means (Table XIV), and n is the number of substations within a station.

TABLE XIII

ERROR TERMS USED TO TEST FOR DIFFERENCES IN THE RATE OF COMMUNITY METABOLISM AMONG DATES WITHIN STATIONS

Source	df	EMS	
		Pg	Rt
Substation x Date within Station I	20	1.24	2.28
Substation x Date within Station II	20	31.67	29.00
Substation x Date within Station III	20	14.67	21.74
Substation x Date within Station IV	20	116.78	194.04

TABLE XIV

ERROR TERMS USED TO TEST FOR DIFFERENCES IN THE RATE OF COMMUNITY METABOLISM AMONG STATIONS AVERAGED OVER ALL DATES

Source	df	EMS	
		Pg	Rt
Substations within Station I	2	0.10	0.04
Substations within Station II	2	1.37	0.91
Substations within Station III	2	1.64	4.80
Substations within Station IV	2	21.10	39.88

Substations provided the best estimate of true experimental error that could be obtained in a reservoir sampling program, although they actually were only subsamples within an area. Substations provided a better estimate of experimental error for some parameters than for others. In general, variation of physicochemical parameters among substations was extremely low and only slightly larger than sampling error. Variation of parameters such as biomass, chlorophyll a, and community metabolism among substations was often large because of patchiness of the plankton population. Patchiness was most pronounced in the surface waters and decreased with depth, with little variation among substations within a sampling area present in the hypolimnion. Patchiness of the phytoplankton population in surface waters primarily was caused by variations in surface current patterns and by shading from bluffs and trees along shores. Plankton "blooms" in Lake Mendota often were created mechanically in regions of near-surface current convergence (Ragotzkie and Bryson 1953). At Station I the reservoir basin was narrow and surface currents were produced primarily by inflowing river water. Surface waters were well mixed and no patchiness of plankton was visible on sampling dates. In downstream sampling areas the reservoir widened, and wind-induced currents were predominant in the surface waters. Patchiness of plankton was most pronounced at Station IV and caused a larger variation among substations than was present in upstream sampling areas. The heterogeneity of error mean squares presented in Tables XIII and XIV suggests that in future studies the number of substations within a sampling area should be increased downstream as the reservoir becomes wider to provide a better estimate of the true population mean.

CHAPTER IV

COMPARISON OF PHYSICOCHEMICAL LIMNOLOGY OF KEYSTONE RESERVOIR DURING THE WATER YEARS 1965-66 AND 1966-67

Differences in Reservoir Operational Procedures

During 1965-67, Keystone Reservoir was operated primarily for flood control and recreational purposes. Except for a few special water releases to facilitate downstream construction, operational procedures were not affected by navigation requirements. Hydroelectric power generation did not begin until 1968, and elevation of discharge intakes was not critical. Water could be released from tainter gates located near the surface of the reservoir or from sluice gates located near the bottom of the reservoir. All discharges from the reservoir were made through tainter gates from August 1965 through July 1966. Because of a build-up of salt-heavy, stagnant water in the lower layers of the reservoir (Eley et al. 1967), operational procedures were changed in July 1966 in an effort to improve water quality. From 15 July through 28 July, water was released through tainter and sluice gates in an attempt to provide acceptable downstream water quality. On 16 July, bottom water released through sluice gates composed only 25% of the total discharge. By 22 July, this proportion had been increased to 80%, and by 29 July, the total discharge was being released through sluice gates. All discharges were made through sluice gates throughout the remainder of 1966-67. In 1968, the generation of hydroelectric power during periods of peak power demand was begun, and water was discharged through power penstocks and sluice gates located near the bottom of the dam.

Differences in Quantity and Quality of Inflowing Water

Quantity and quality of inflowing water are as important as operational procedures in the physicochemical limnology of main-stem reservoirs. Typical main-stem impoundments alter the original configuration of streams much less than storage reservoirs do, and much of the impounded water is restricted to the original channel, although backwater may extend into valleys of tributary streams to form large embayments in the downstream end of reservoirs (Kittrell 1959). Retention time of water usually is a few days to a few weeks and is controlled primarily by the quantity of inflows. High inflows often create turbulence throughout main-stem reservoirs and may upset stratification established during periods of low inflow. Density of inflowing water is determined by temperature and the load of dissolved and suspended solids and may be different than densities of impounded water. Inflows may enter reservoirs as overflows, interflows, or underflows (Love 1961).

Water quality and discharge records of the U. S. Geological Survey show striking differences between annual means of the Cimarron and Arkansas Rivers and between the water years 1965-66 and 1966-67 (Table XV). The Cimarron River at Perkins, Oklahoma, contained a concentration of dissolved solids about four times the concentration of dissolved solids in the Arkansas River at Ralston, Oklahoma. The

TABLE XV

COMPARISON OF WATER QUALITY AND DISCHARGE OF THE CIMARRON AND ARKANSAS RIVERS*

Water Year	Location	Discharge $m^3\ sec^{-1}$	Conductivity µmhos	Dissolved Solids $g\ m^{-3}$	Na $g\ m^{-3}$	Cl $g\ m^{-3}$	SO_4 $g\ m^{-3}$	Cl/SO_4 Ratio	NO_3-N $g\ m^{-3}$	PO_4-P $g\ m^{-3}$	HCO_3 $g\ m^{-3}$	pH
10/65-9/66	Cim. R. at Perkins	10.5	9320	5580	1840	2890	331	8.7	0.79		186	8.2
	Ark. R. at Ralston	51.2	1960	1210	267	366	282	1.3	0.79		180	8.3
	Ark. R. below Keystone	73.8	2800	1530	433	640	288	2.8	0.29		133	8.2
10/66-9/67	Cim. R. at Perkins	14.6	6020	2970	986	1510	174	8.7		0.25	135	8.3
	Ark. R. at Ralston	66.3	1020	621	132	200	86	2.3	0.68	0.31	135	8.3
	Ark. R. below Keystone	96.9	2240	1280	369	567	131	4.3	0.38	0.09	132	8.3

---

*Concentrations, µmhos, and pH are discharge-weighted averages, and discharges are time-weighted averages taken from U. S. Geological Survey Water Quality Records for 1966 and 1967. Differences in discharge values given in this table and Table III are due to omission of September 1965 in the U.S.G.S. 1965-66 water year. During 1965-66, 30% of the total precipitation to the contributing drainage area fell in September.

difference in concentrations of dissolved solids between the two rivers largely was due to high concentrations of NaCl in the Cimarron River. Concentrations of Na ion and Cl ion in the Cimarron River were about 7 times greater than concentrations in the Arkansas River. The concentration of SO_4 ion in the Cimarron River was only one to two times greater than the concentration in the Arkansas River. These differences resulted in a Cl/SO_4 ratio for the Cimarron River of approximately nine while the Arkansas River had a ratio between one and three. Bicarbonate was the other major anion besides Cl and SO_4. Other major cations were Ca, Mg, and K, although they occurred in much lower concentrations than Na ion. Mineralization of the Arkansas River below Keystone Dam was intermediate to that of the Cimarron and Arkansas Rivers above Keystone. A notable effect of impoundment on the physicochemical parameters shown in Table XV was the large reduction in concentrations of nitrate nitrogen and phosphate phosphorus.

Differences in Quality of Reservoir Water

In general, water quality of Keystone Reservoir was better in all respects during 1966-67 than during 1965-66. Significant differences in physicochemical conditions were present among sampling stations within years, between years within stations, and between years averaged over all stations (Table XVI). Station x date error mean squares were used to test for significant differences among treatment means (Table XVII). Replicate observations of temperature and dissolved oxygen were made during 1966-67, and station x date interactions were highly significant ($\alpha = 0.01$). Station x date interactions probably were present for all physicochemical parameters during both years, and interaction

TABLE XVI

DIFFERENCES IN WATER QUALITY BETWEEN WATER YEARS 1965-66 AND 1966-67 AND AMONG SAMPLING LOCATIONS IN KEYSTONE RESERVOIR

Parameter	Water Year	Station I $\bar{X}$		Station II $\bar{X}$		Station III $\bar{X}$		Station IV $\bar{X}$	$\bar{\bar{X}}$
Temperature (C)	1965-66	16.13		16.55	*	15.47		15.19	15.83
	1966-67	15.68		16.28		16.04		15.74	15.93
Conductivity (μmhos)	1965-66	10208.33	**	2994.94	**	2910.50		3275.59	4847.34
		**							*
	1966-67	7884.63	**	3147.47		2569.17		2490.47	4022.93
Turbidity Units	1965-66	226.83	**	43.96	**	29.11		22.23	80.53
		**							**
	1966-67	139.62	**	42.94	*	27.21		30.15	59.95
g O_2 m^{-3}	1965-66	8.35		7.94		7.98	*	7.14	7.85
		**		**					*
	1966-67	10.10		9.30	*	8.30		8.00	8.90
g HCO_3 m^{-3}	1965-66	86.42	**	94.58	**	106.97	**	116.19	101.04
		**		*		**		*	**
	1966-67	96.00		100.27	**	113.43	**	120.42	107.53
g CO_3 m^{-3}	1965-66	16.67	*	11.03		7.42		8.06	10.80
		**							
	1966-67	41.18	**	15.27		9.73		6.09	16.07
g CO_2 m^{-3}	1965-66	0.57		1.05	**	2.96		3.20	1.94
	1966-67	0.31		0.83	**	2.34		2.52	1.50
pH	1965-66	8.50	**	8.23		8.19	*	8.04	8.21
						*			
	1966-67	8.58	**	8.29		8.34	**	8.00	8.30

* and ** indicate statistically significant differences (α = 0.20 and 0.10, respectively) between means using error terms presented in Table XVII.

TABLE XXI

HERITABILITY ESTIMATES AND STANDARD ERRORS OBTAINED FROM REGRESSION OF OFFSPRING MEAN ON SIRE, DAM, AND MID-PARENT

Trait	Number of Litters	Regression of offspring mean on:		
		Sire	Dam	Mid-Parent
Pig birth weight	353	0.062 ± 0.092	0.034 ± 0.096	0.050 ± 0.066
Pig weight at 21 days of age[a]	174	0.256 ± 0.032	-.122 ± 0.032	0.060 ± 0.054
Pig weight at 42 days of age	349	0.128 ± 0.090	0.064 ± 0.094	0.098 ± 0.065
Post-weaning average daily gain[b]	340	0.234 ± 0.090	0.118 ± 0.116	0.185 ± 0.070
Age at 200 pounds[b]	340	0.240 ± 0.098	0.160 ± 0.124	0.230 ± 0.080
Probe backfat thickness[b]	314	0.318 ± 0.098	0.308 ± 0.086	0.363 ± 0.068

[a] Includes only those pigs born after 1965 Fall.

[b] Female offspring only.

al., 1946; Louca and Robison, 1967) have reported similar results for the heritability of birth weight. This would suggest that pig birth weight is largely a reflection of maternal environment.

Pig 21 Day Weight

Heritability estimates for pig weight at 21 days of age obtained from regression of offspring on sire were significantly higher than those obtained from regression of offspring on dam. The negative estimate obtained from regression of offspring on dam suggests that the heritability of this trait is low or near zero. Falconer (1960) states that, in general, the regression on mid-parent values yields a more precise estimate of heritability for a given total number of individuals measured. The estimates obtained from regression of offspring on mid-parent would also suggest that heritability of pig weight at 21 days of age is near zero. However, in this study, the sampling variance associated with mid-parent values was as large or larger than that associated with sire or dam values. No apparent explanation for the higher estimate obtained from regression of offspring on sire is available.

Pig weight at 21 days of age should be affected more by the maternal environment than pig weight at birth or weaning. The degree to which mothering ability and maternal environment are associated with pig weight at 21 days is probably the primary reason for the lower estimate of heritability obtained from offspring-dam analysis. Very few studies have been conducted where pig weight at 21 days of age was obtained. Therefore, other estimates are unavailable for comparison purposes.

Pig 42 Day Weight

Estimates of the heritability of weaning weight obtained in this study are in general agreement with those found in the literature. Cunningham (1969) reviewed 16 estimates of the heritability of weaning weight and found a range of -.18 to 0.24 with a simple average of 0.08. Again, the results obtained in this study would suggest that very little additive genetic variance exists for pig weaning weight.

Average Daily Gain

Estimates in the literature for heritability of average daily gain range from -.09 (Louca and Robison, 1967) to 0.77 (Biswas *et al.*, 1966). The difference in growth periods in which average daily gain is measured could be partly responsible for this wide range in estimates.

Estimates obtained in this study (0.118 ± 0.116 to 0.288 ± 0.061) are somewhat lower than those reported by some workers but are in general agreement with the average of all estimates found in the literature. Louca and Robison (1967) studied the heritability of average daily gain in different growth periods. Their estimates ranged from -.09 ± 0.10 for average daily gain from 140 days to puberty to 0.34 ± 0.17 for average daily gain from 42 to 140 days of age. Most of the available literature indicate moderate heritabilities (0.20 to 0.30) for average daily gain.

Although not significantly different, the estimates obtained from regression of offspring mean on parent (or mid-parent) were slightly lower than estimates obtained from individual offspring on parent (or mid-parent). These observed differences could be a reflection of the method of regression analysis. If the sire or dam of a large litter had a superior (or inferior) growth rate, then the parent performance would reductions in annual mean water temperatures resulting in greater solubility of oxygen. The change in reservoir discharge level resulted in a reduction of anoxic hypolimnion although significant differences between annual mean concentrations of oxygen at Stations III and IV could not be demonstrated between the two years using station x date EMS. Significant increases in bicarbonate ion concentration at all stations between the years 1965-66 and 1966-67 may have been due to an increase in the average bicarbonate concentration of inflowing waters. The release of hypolimnetic water as opposed to epilimnetic water would be expected to cause a decrease rather than an increase in bicarbonate ion concentration.

Effects of Discharge Level on Stratification and Density Flows

Stratification

Differences in operational procedures of Keystone Reservoir between 1965-66 and 1966-67 produced marked differences in winter and summer stratification patterns (Fig. 13). During the fall and winter of 1965-66 when all reservoir discharges were made from the epilimnion, a build-up of highly mineralized Cimarron River water in the hypolimnion produced meromictic conditions in the reservoir. The chemocline was located at a depth of about 12 m, and specific conductance increased 8,000 µmhos from the top to the bottom of the monimolimnion. The lower layers were not entirely anoxic during the winter indicating partial mixing across the chemocline or importation of aerated Cimarron density flows sufficient to prevent complete oxygen depletion. Conditions in Keystone during 1965-66 would be termed partial meromixis

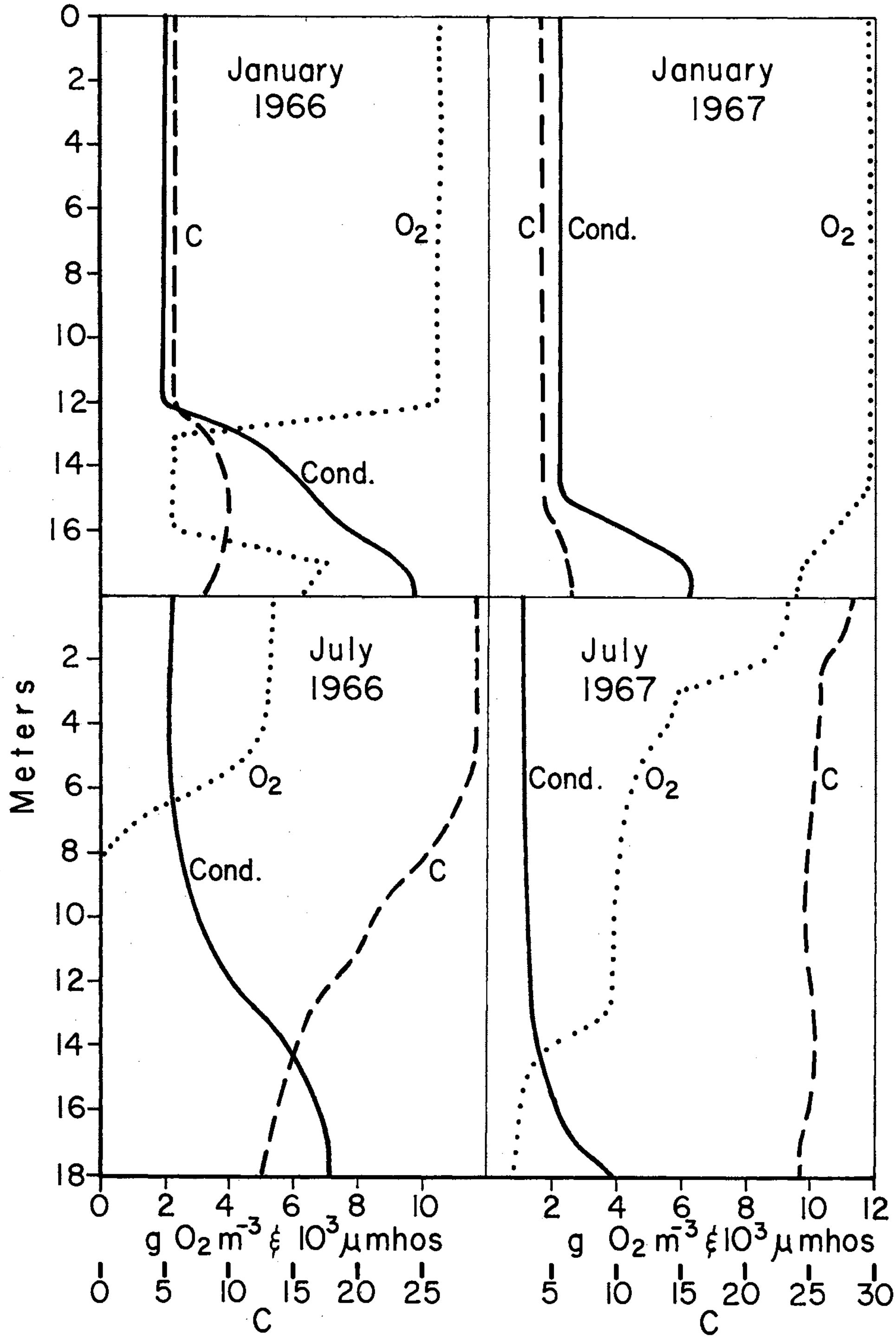

Figure 13. Winter and summer extremes of stratification at Station IV during 1966 and 1967

(Carter 1967). The meromixis in Keystone Reservoir during 1965-66 does not strictly meet the definitions of either ectogenic or crenogenic meromixis (Hutchinson 1937), because the inflow of mineralized Cimarron River water cannot be classified as an external "catastrophe" as in ectogenic meromixis nor can the inflows be considered equivalent to internal saline springs as in crenogenic meromixis. Keystone Reservoir and ectogenic and crenogenic meromictic lakes of North America have "marine" characteristics or an "alkali-evaporite" affinity, with low Ca/Mg ratios in comparison to Na/K ratios, Cl and SO_4 as the dominant anions, and an average pH greater than 7.8 (Table XVIII). Holomictic lakes and reservoirs and biogenic meromictic lakes of North America are essentially "fresh water" types with respect to water chemistry, with Ca/Mg ratios equal to or higher than Na/K ratios, bicarbonate as the major anion and chloride conspicuously low, and an average pH less than 7.8 (Livingstone 1963).

Meromixis produced mesothermy and a negative heterograde oxygen distribution in January 1966, with maximum temperature and minimum dissolved oxygen concentration occurring between 13 and 16 m of depth (Fig. 13). Temperature stratification in January 1966 was in contrast with the characteristic dichothermy of meromictic lakes. The unusual distributions of temperature and oxygen during the winter of 1965-66 were caused by the chemocline preventing convection currents produced by surface cooling from entering the monimolimnion and reoxygenating and cooling water below 12 m. During a period of low flow extending from December 1965 through March 1966, the highly mineralized Cimarron River formed an underflow along the bottom of the Cimarron arm and brought cooler, aerated water into the bottom of the monimolimnion.

TABLE XVIII

COMPARISON OF CATION RATIOS OF KEYSTONE RESERVOIR WITH RATIOS OF ECTOGENIC, CRENOGENIC, AND BIOGENIC MEROMICTIC LAKES AND SEA WATER

Location	Date	Depth (m)	Cation Ratios Ca/Mg	Cation Ratios Na/K
Sea Water[a]			0.32	27.7
Hot Lake, Wash.[a] (ectogenic)		0	0.03	8.2
Soap Lake, Wash.[a] (ecto-crenogenic)		0	0.20	12.1
		16	0.04	22.1
Fayetteville Green Lake, New York[a] (biogenic)		0	6.1	4.3
		50	5.9	5.8
Keystone Reservoir	3/66	0	2.9	37.2
		18	3.0	120.6
	8/66[b]	0	2.8	62.8
		22	2.8	101.3
	5/67[b]	0	3.2	70.3
		18	2.9	105.1
	7/67[b]	0	4.1	33.6
		22	3.3	47.6

[a] From Likens (1967).

[b] Calculated from Falls (1969).

Intrusions of density flows with high oxygen concentrations into the hypolimnion of reservoirs have been observed in Norris Reservoir (Wiebe 1938), Cherokee Reservoir (Lyman 1944), Boone Reservoir (Churchill 1957), and Tenkiller Reservoir (Summers 1961).

No spring turnover occurred in 1966, and surface warming during the spring and summer months produced stable thermal stratification imposed upon chemical stratification already present (Fig. 13). In July 1966, the thermocline was located between 5 and 6 m of depth, resulting in an extreme clinograde oxygen distribution with anoxia occurring below 8 m. Inflows from the Cimarron River during the spring and summer of 1966 were less mineralized than winter inflows and entered the reservoir as interflows between the less dense epilimnion and denser hypolimnion. Mixing of spring and summer interflows with more highly mineralized water from winter inflows decreased conductivity below 16 m by 2500 μmhos (Fig. 13). Conductivity of water below the thermocline and above 12 m of depth was increased.

Temporary monimolimnions formed by build-ups of high concentrations of dissolved solids in "akinetic spaces" have been observed in South Holston Reservoir of the TVA (Churchill 1957) and in Klicava, Slapy, and Kruzberk Reservoirs of Czechoslovakia (Fiala 1966). The formation of a monimolimnion in South Holston Reservoir in 1964 resulted from continued releases of water from the upper layers of the reservoir. Akinetic spaces observed in reservoirs of Czechoslovakia resulted from epilimnetic discharges and the presence of "inner dams" located behind regular dams to insure a minimum water storage during times of extreme reservoir drawdown.

A program to drain off the stagnant hypolimnion of Keystone Reservoir was initiated by the U. S. Army Corps of Engineers in July 1966 in an attempt to improve reservoir water quality. Release of hypolimnetic water had an immediate effect upon chemical stratification in the reservoir (Fig. 14). Complete mixing of reservoir water occurred during the last week of September 1966. During the winter of 1966-67, the reservoir was completely mixed to a depth of 15 m (Fig. 13). A highly mineralized, density current of Cimarron River water flowed along the bottom of the Cimarron arm of the reservoir during the winter of 1966-67, but the dense underflow was discharged through sluice gates and no build-up occurred.

Warming of surface waters during May 1967 resulted in thermal stratification (Fig. 15). Stratification was not stable and high inflows during June 1967 produced rapid warming of the entire water mass. A temperature difference between the epilimnion and hypolimnion of only 4 C existed in July 1967 as compared to a difference of 17 C in July 1966 (Fig. 13). The small thermal gradient at high temperatures produced a density difference sufficient to prevent wind action from completely mixing the water mass. A combination of stable thermal stratification above 5 m of depth and relatively stable chemical stratification below 14 m resulted in an unusually shaped clinograde oxygen distribution (Fig. 13). Three regions of uniform oxygen concentration were separated by regions of rapid oxygen depletion between 2 and 3 m of depth and between 13 and 14 m of depth.

Isotherms (Fig. 15) and isolines of conductivity (Fig. 16), dissolved oxygen (Fig. 17), and pH (Fig. 18) indicate seasonal patterns of stratification during 1965-67. Vertical or sharply dipping isotherms

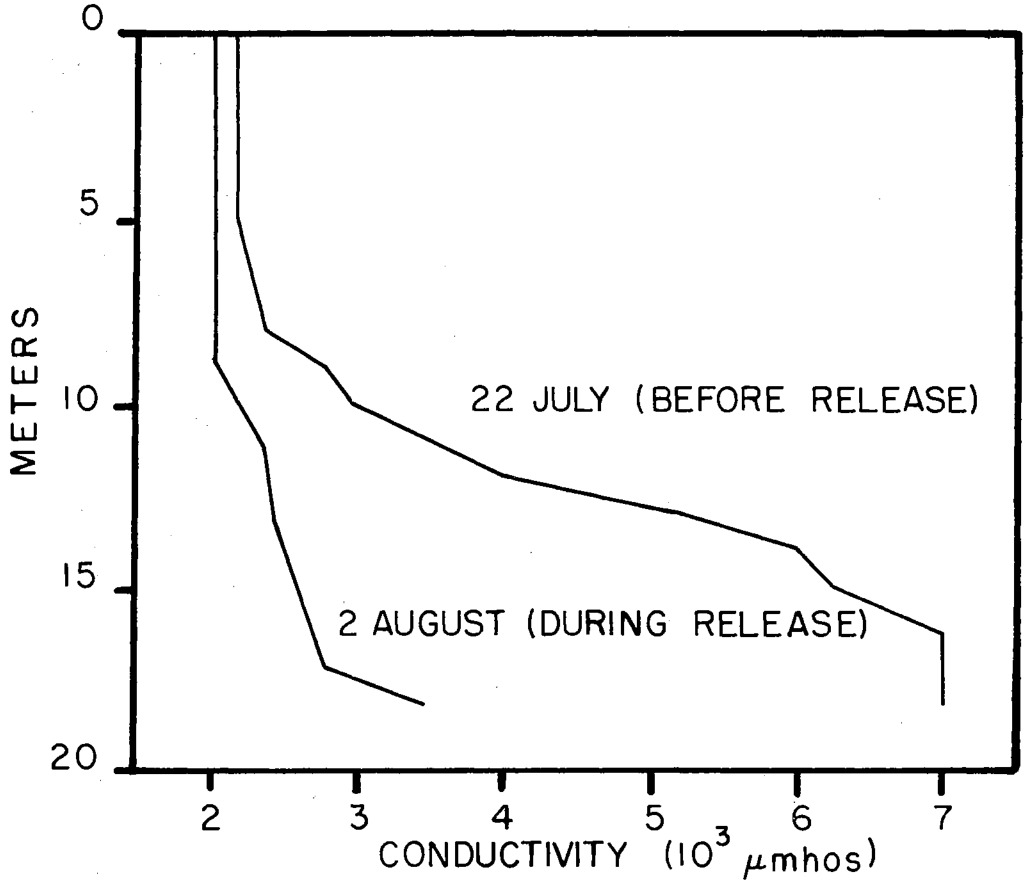

Figure 14. Effect of release of hypolimnetic water on conductivity in Keystone Reservoir, 1966

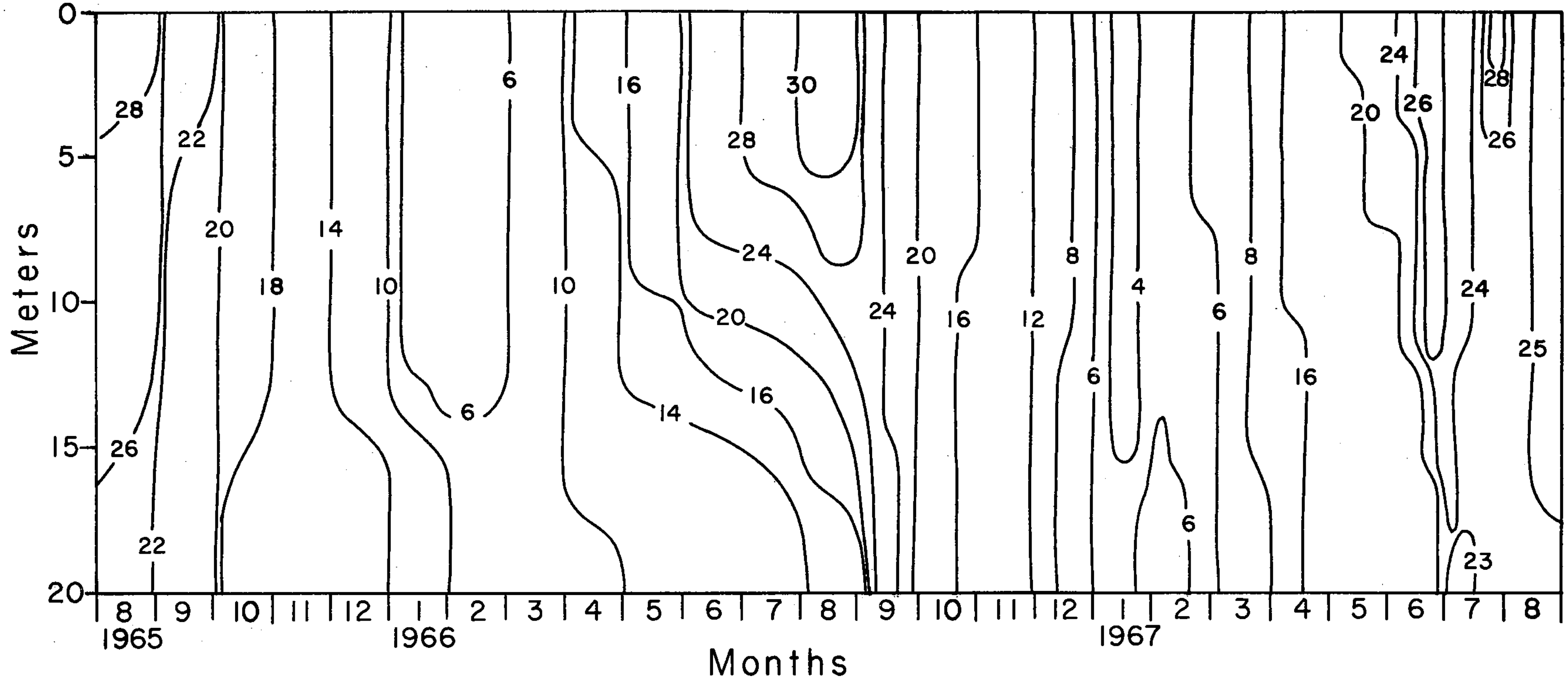

Figure 15. Isotherms of temperature (C) in Keystone Reservoir during 1965-67

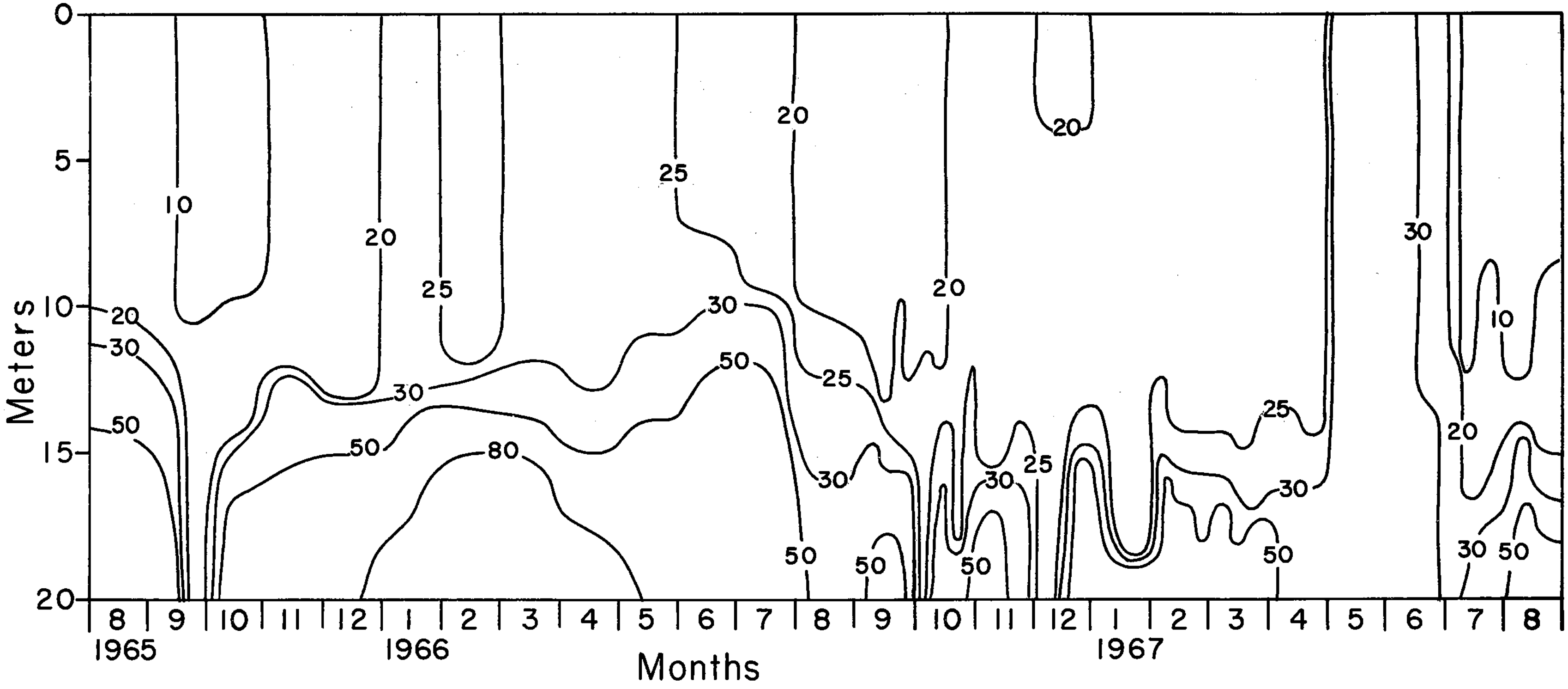

Figure 16. Isolines of conductivity (10^2 μmhos) in Keystone Reservoir during 1965-67

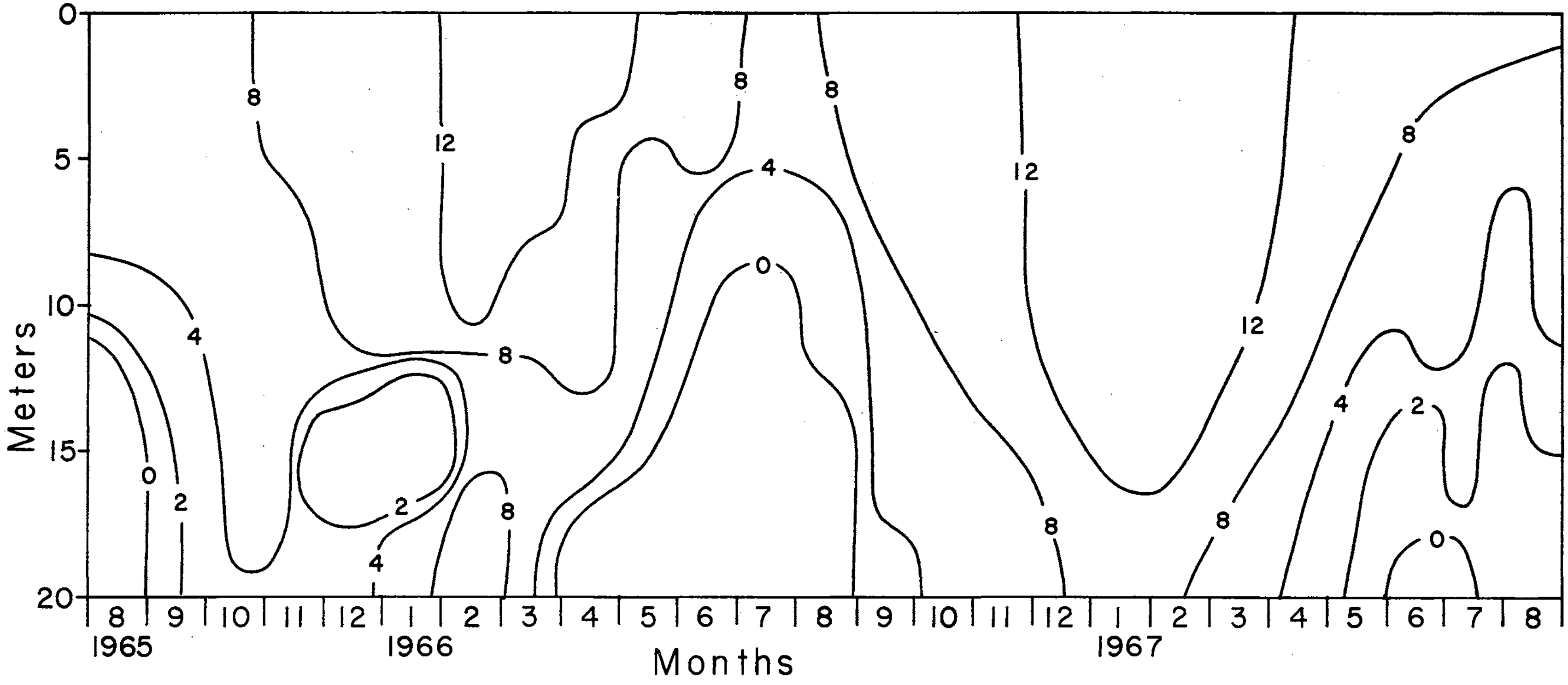

Figure 17. Isolines of dissolved oxygen concentration (g O_2 m^{-3}) in Keystone Reservoir during 1965-67

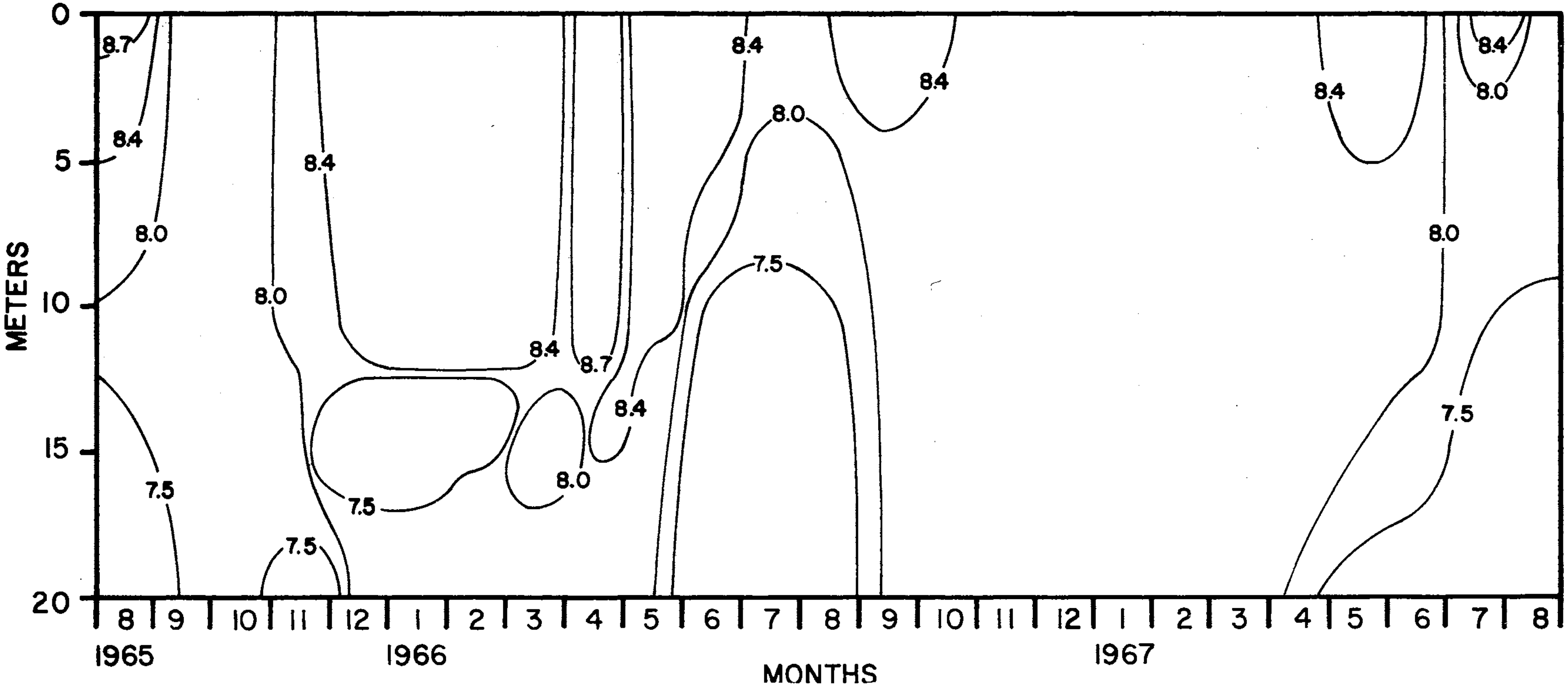

Figure 18. Isolines of pH in Keystone Reservoir during 1965-67

and isolines between September and October 1965 and between June and July 1967 illustrate upsetting of stratification by floods. Effects of the flood of September 1965 have been described by Carter and Eley (1967). Significant stratification was present during August and the first half of September 1965 (Fig. 16, 17, 18). Floodwaters upset chemical stratification and aerated the anoxic hypolimnion, but the large oxygen demand of organic matter contained in floodwaters decreased the oxygen content of bottom waters after high inflows subsided (Fig. 17). Immediately after the flood, chemical stratification was re-established, and the build-up of highly mineralized Cimarron River water in the hypolimnion continued from October 1965 until July 1966 (Fig. 16). An underflow of extremely dense Cimarron River water began in the last half of December 1965 and continued through April 1966.

Inflows of Cimarron River water were of variable quality between July and December 1966. Because of the continual draining of dense bottom water, chemical stratification was not sufficient to prevent a fall overturn between September and October 1966. The underflow of Cimarron River water between December 1966 and April 1967 was less conductive than the underflow between December 1965 and April 1966 (Fig. 16). The duration of the negative heterograde oxygen distribution shown in Fig. 13 is demonstrated by the size of the circle formed by isolines of dissolved oxygen and pH in the hypolimnion between November 1965 and March 1966 (Fig. 17 and 18).

Analyses of variance among average monthly differences in temperature and conductivity of surface and bottom water at Stations II, III, and IV demonstrated statistically significant differences between intensity of stratification during 1965-66 and 1966-67 (Tables XIX and XX). Differences between surface and bottom temperatures averaged over all dates varied from 1.7 C at Station II to 3.2 C at Station III during 1965-66 and varied from 1.0 C at Station II to 1.6 C at Station IV during 1966-67 (Fig. 19). Thermal stratification was most intense during May, June, and July of both years. The sharp decrease in thermal stratification between June and July 1967 was caused by floodwaters flowing through the reservoir during the last half of June. Effectiveness of the change in discharge level in reducing thermal stratification is shown by the smaller temperature gradient during all months of 1966-67 than during 1965-66 except November (Fig. 19). No month x year interaction was present for temperature, indicating that thermal stratification followed a similar pattern during both years and the change in discharge level reduced intensity of thermal stratification but did not alter the seasonal pattern.

The change in discharge level had a notable effect on the intensity of the chemical stratification (Fig. 20). Intensity of chemical stratification was significantly less during all months of 1966-67 than during months of 1965-66, except July and August. An inflow of highly mineralized Cimarron River water into the hypolimnion of the reservoir during July and August 1967 (Fig. 16) increased the intensity of chemical stratification (Fig. 20). The large difference in conductivity of the epilimnion and hypolimnion in August 1967 also was caused by highly dilute water from the June flood remaining in the epilimnion. Differences in the pattern of chemical stratification during July and August of 1966 and 1967 resulted in a significant month x year interaction for conductivity (Table XX).

TABLE XIX

SPLIT PLOT ANALYSIS OF VARIANCE AMONG MONTHLY AND ANNUAL MEAN DIFFERENCES IN SURFACE AND BOTTOM TEMPERATURE OF KEYSTONE RESERVOIR DURING 1965-66 AND 1966-67 AVERAGED OVER STATIONS II, III, AND IV

Source of Variation	df	MS	Calculated F
Total	71		
Main-plot analysis			
year	1	23.2334	5.94*
station + station x year	4	3.9139	
Sub-plot analysis			
month	11	11.2256	5.89**
month x year	11	1.9729	1.03
station x month + station x month x year	44	1.9069	

* and ** indicate significant differences ($\alpha = 0.10$ and 0.01, respectively) among means.

TABLE XX

SPLIT PLOT ANALYSIS OF VARIANCE AMONG MONTHLY AND ANNUAL MEAN DIFFERENCES IN SURFACE AND BOTTOM CONDUCTIVITY OF KEYSTONE RESERVOIR DURING 1965-66 AND 1966-67 AVERAGED OVER STATIONS II, III, AND IV

Source of Variation	df	MS	Calculated F
Total	71		
Main-plot analysis	5		
year	1	97969669.00	27.66**
station + station x year	4	3540816.95	
Sub-plot analysis	66		
month	11	8297405.69	5.97**
month x year	11	10291387.12	7.41**
station x month + station x month x year	44	1389311.19	

** indicates significant differences ($\alpha = 0.01$) among means.

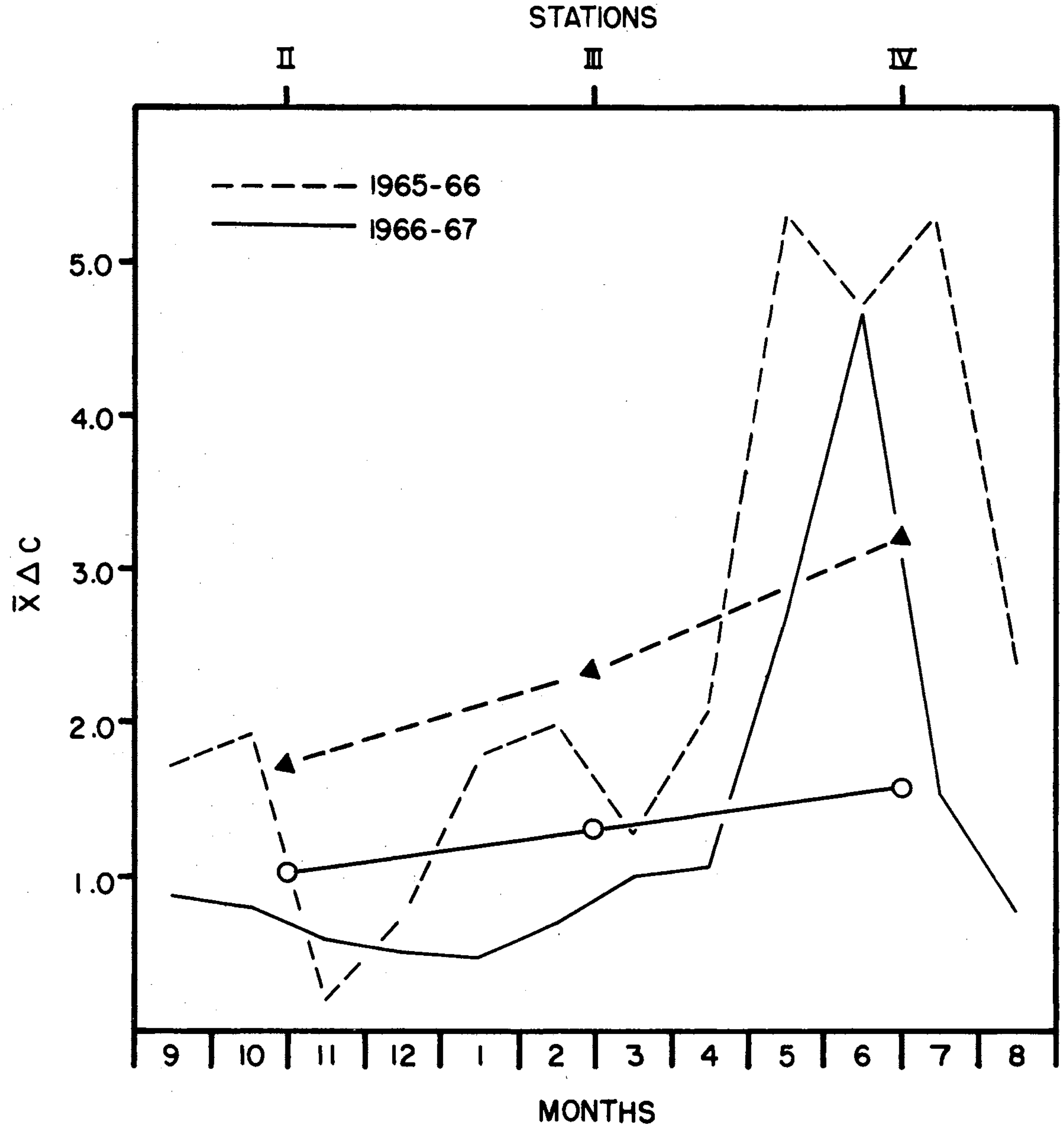

Figure 19. Comparison of monthly and station mean differences in surface and bottom temperature of Keystone Reservoir during 1965-66 and 1966-67

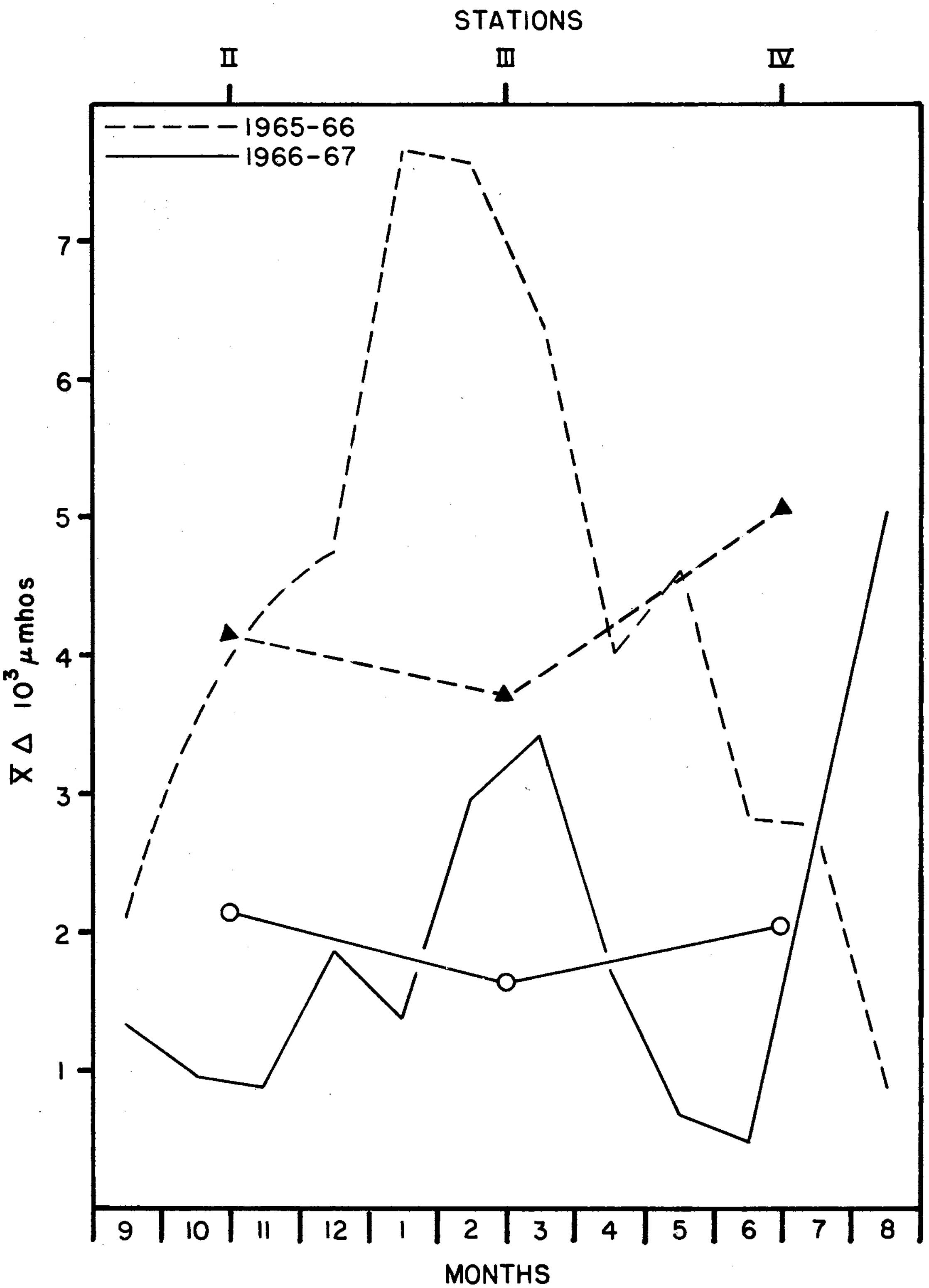

Figure 20. Comparison of monthly and station mean differences in surface and bottom conductivity of Keystone Reservoir during 1965-66 and 1966-67

Density Flows

Density flows were first detected by their high specific conductance in Keystone Reservoir (Eley et al. 1967). During the winter of 1966, highly mineralized Cimarron River water entered the reservoir as an underflow along the Cimarron arm (Fig. 21). Since all discharges from the reservoir during 1965-66 were made through tainter gates located near the surface, dense Cimarron water build-up in volume in the hypolimnion and flowed up the Arkansas arm, undercutting lighter Arkansas River water. Highly conductive water of Cimarron River origin was found in the bottom of the Arkansas arm 15 km above the dam during March 1966 (Fig. 21). During periods of heavy precipitation, the Cimarron River entered the reservoir as an interflow or overflow. During dry periods of 1966-67, the Cimarron River again entered the reservoir as a dense underflow. The density current flowed along the bottom of the Cimarron arm and was released through the dam because all reservoir discharges were made through sluice gates (Fig. 21). No significant build-up of dense bottom water occurred, but 2000, 2400, and 3000 μmhos isolines of conductivity in Fig. 21 suggest that flows partially composed of water of Cimarron River origin were occurring up the bottom of the Arkansas arm in 1967.

Because of the distinct Cl/SO_4 ratios of the Cimarron and Arkansas Rivers (Table XV), occasional surveys of Cl and SO_4 concentrations in the reservoir were made in an effort to identify the origin of various reservoir water masses (Fig. 22). In September 1965 and in January and May 1966, the water mass of the bottom 5 m of the entire Cimarron arm and below 12 m of depth for approximately 17 km up the Arkansas arm was primarily of Cimarron River origin. All water above 12 m of depth

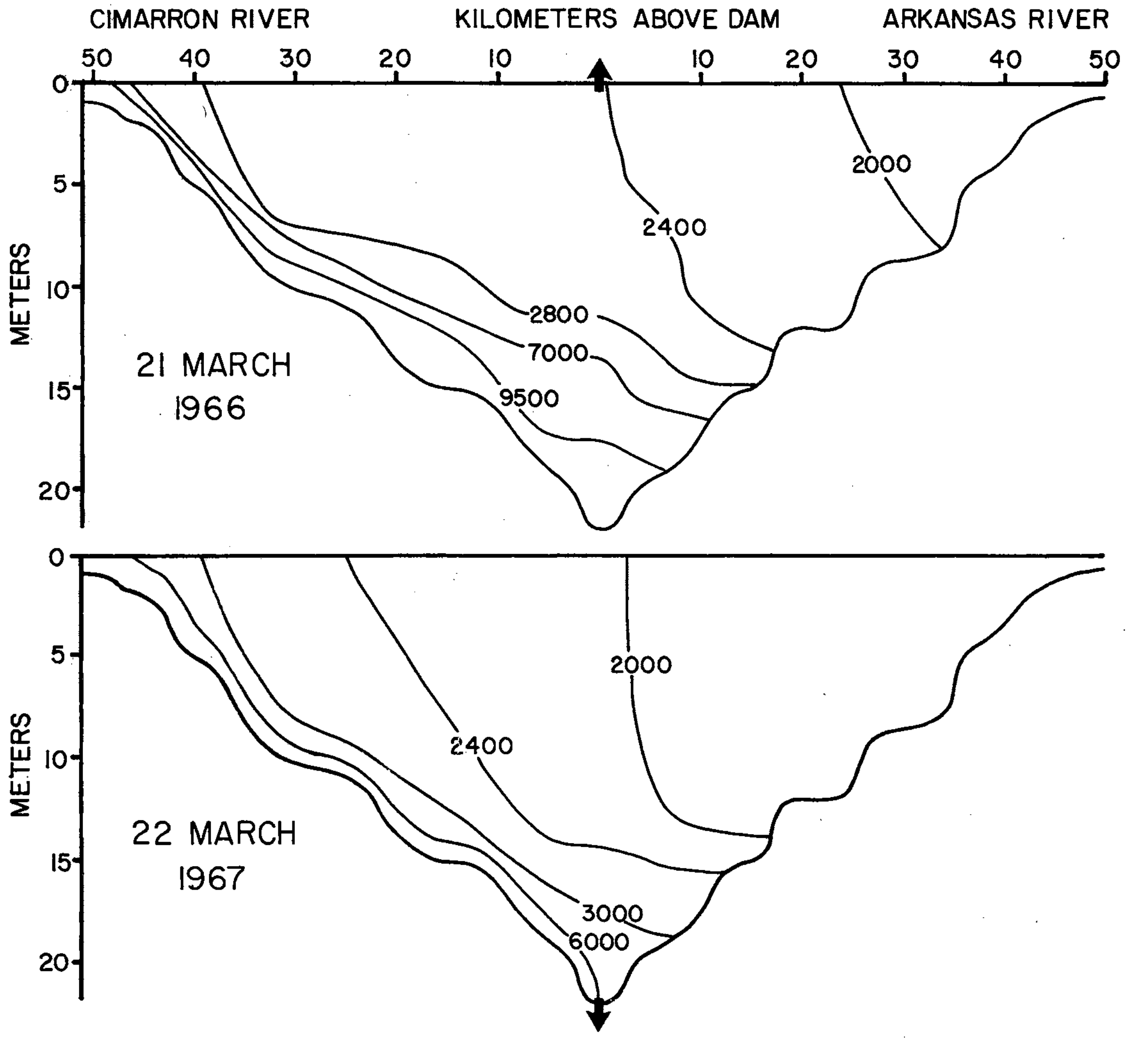

Figure 21. Isolines of conductivity (μmhos) showing density flows in Keystone Reservoir during 1966 and 1967. Arrows indicate the level at which water was being discharged through the dam.

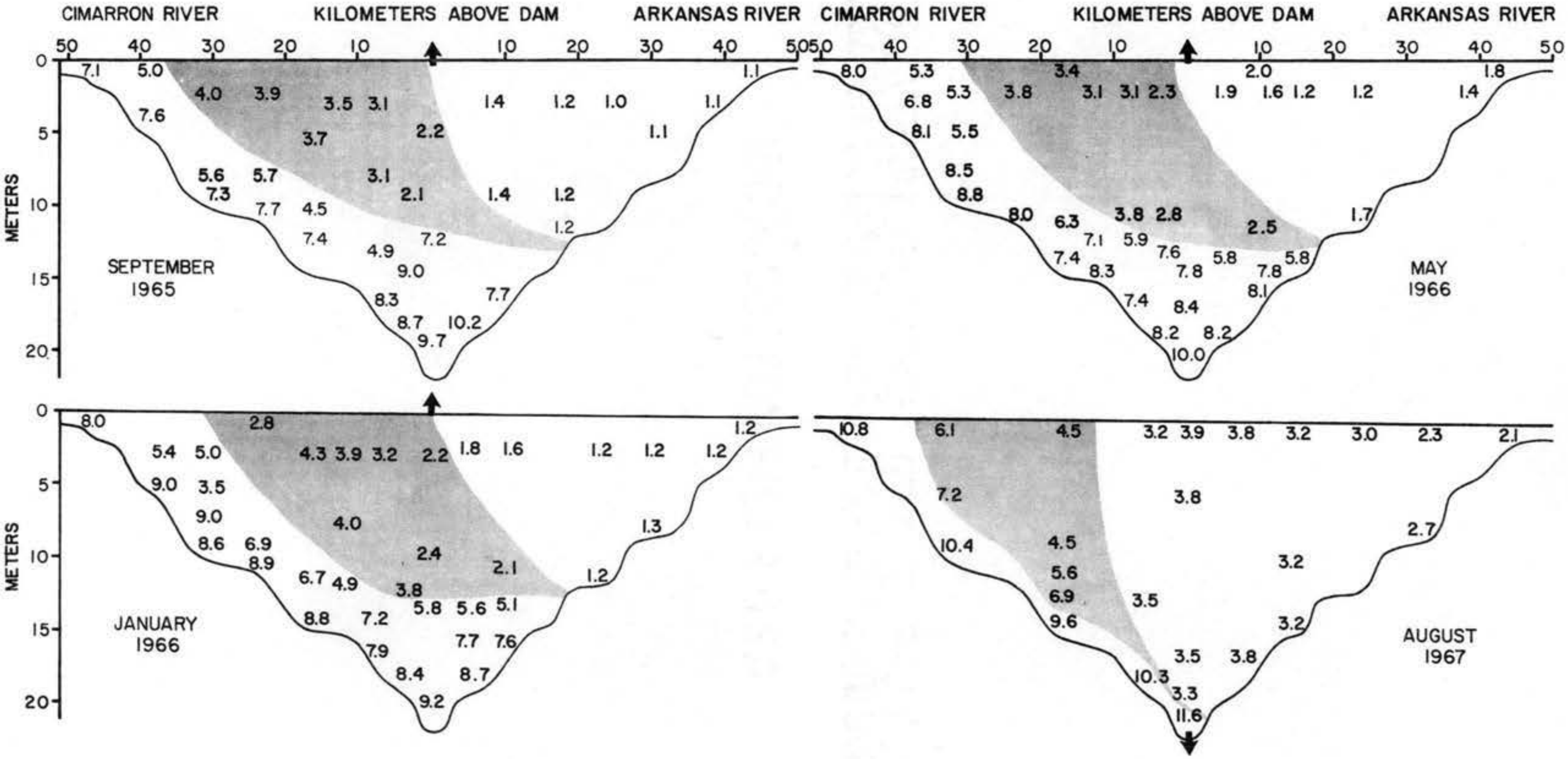

Figure 22. Chloride/sulfate ratios in Keystone Reservoir during 1965-67. High ratios identify water primarily of Cimarron River origin while low ratios identify water contributed by the Arkansas River. Shaded areas indicate zones of mixing.

in the Arkansas arm was primarily of Arkansas River origin except for a small section in the lower one-third of the arm. The large water mass lying between water primarily of Cimarron River origin and water primarily of Arkansas River origin apparently was a zone of mixing, as indicated by intermediate Cl/SO_4 ratios. In August 1967, one year after the change in level of reservoir discharge from the epilimnion to the hypolimnion, the proportion of water in the reservoir primarily of Arkansas River origin had greatly increased (Fig. 22). Water primarily of Cimarron River origin was confined to an underflow along the bottom of the Cimarron arm. The zone of mixing shifted entirely into the Cimarron arm of the reservoir as indicated by the wedge of intermediate Cl/SO_4 ratios in the mid-reaches of the Cimarron arm (Fig. 22).

Velocity and Direction of Water Currents

Methods of Measurement

A modification of the free-drag method used by the University of Wisconsin was adopted for use in estimating the velocity and direction of surface and sub-surface currents in Keystone Reservoir. Modifications included using 1 x 60 x 60 cm plywood boards instead of 6-oz milk cans as floats for the drag, and using four 30 cm^2 metal blades instead of four 10 x 15 cm blades to construct vanes (Fig. 23). These modifications increased the area ratio of vane to float from 20:1 to 30:1 and reduced exposure of float above the water surface. The large area ratio of vane to float reduced errors in estimating the velocity and direction of sub-surface currents caused by opposing surface currents. For example, if surface and sub-surface currents of an equal velocity of 100 m min^{-1} were traveling in opposite directions, the estimate of

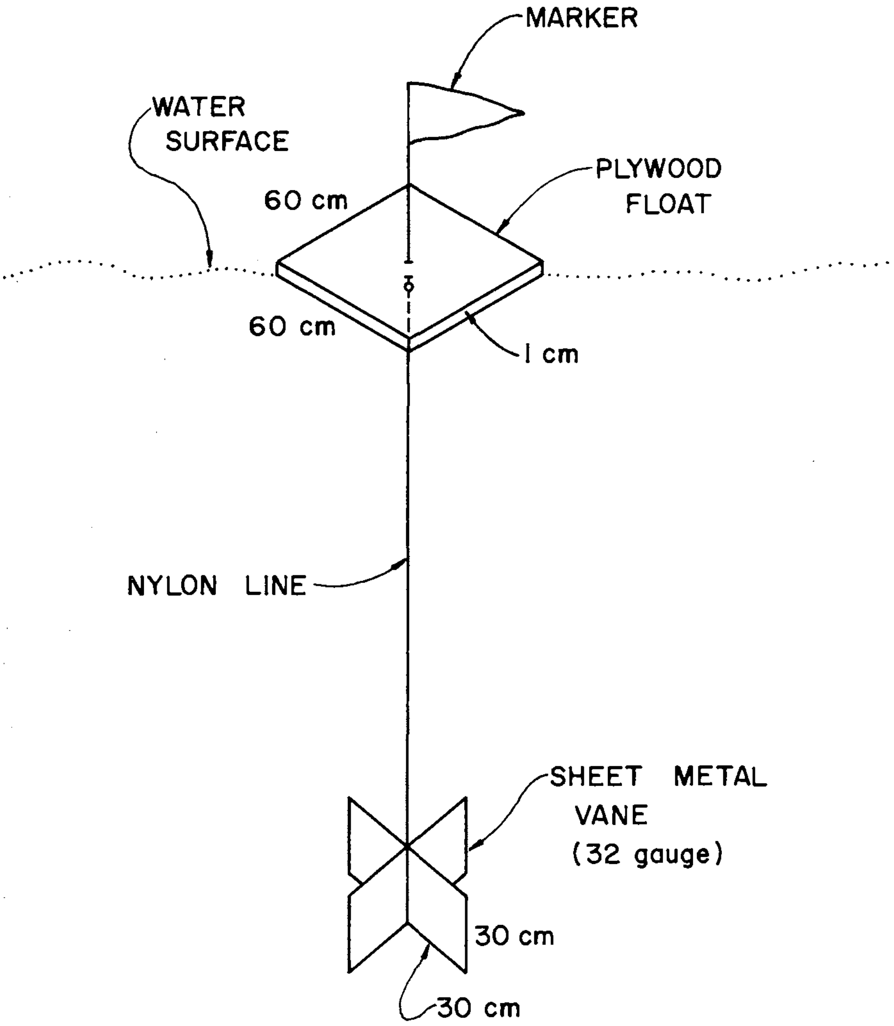

Figure 23. Free-drag used to measure velocity and direction of subsurface currents in Keystone Reservoir. Surface currents were measured by attaching a metal vane directly to a plywood float.

velocity of the sub-surface current would be 97 m min^{-1}, resulting in an error of only 3%. Changes in the location of drags over known intervals of time were plotted by triangulation from sightings by two plane tables with alidades located at each end of a baseline established on shore. Telescopic alidades were not available, and all current measurements were made within 400 m of shore so that visual sightings could be made.

A comparison of estimates of the velocity and direction of surface currents obtained using free-drags and uranine dye plumes was made to test the accuracy of the free-drag method (Fig. 24). Estimates made by dye plumes and free-drags agreed closely in speed and direction, but defining the perimeter of dye plumes was more difficult than sighting free-drags. Dye plumes became elongated parallel to the direction of surface currents (Fig. 24). This elongation has been interpreted as vertical differential advection due to a shearing current (Ichiye 1965). Dye plumes in Keystone Reservoir did not possess the characteristic curvature of the tail part of the dye patch which is commonly observed in ocean studies. Dye plume curvature normally has been attributed to Ekman spirals produced by the Coriolis effect in pure wind currents (Ichiye 1965). Absence of clockwise curvature of surface currents in Keystone Reservoir probably was due to the lack of depth and high eddy viscosity (personal communication from R. A. Bryson, University of Wisconsin).

Velocity of Currents

The average velocity of 211 observations on currents in Keystone Reservoir by the free-drag method was 3.02 ± 0.44 m min^{-1}, with an

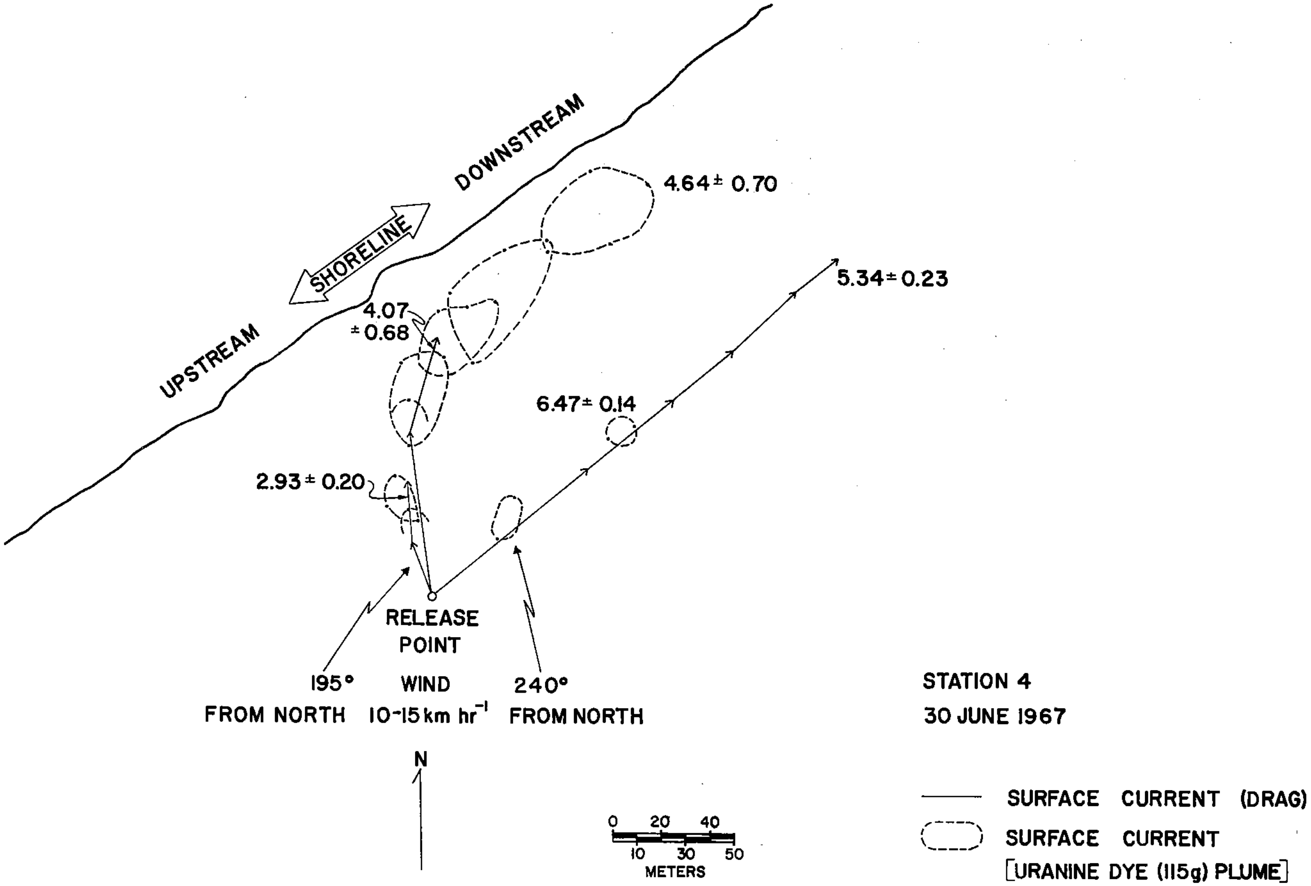

Figure 24. Comparison of the speed (m min^{-1}) and direction of surface currents as estimated by the free-drag and dye plume methods

average coefficient of variation of 14.6% (Table XXI). Average current velocities ranged from a high of 5.10 ± 0.58 at the surface to a low of 1.65 ± 0.22 at 14 m of depth and increased again to 3.84 ± 0.54 at 18 m of depth. The high velocity of surface currents was primarily caused by observations made in surface waters when wind driven currents were in the direction of mass flow (Fig. 25). Occasionally wind velocities were sufficient to cause surface currents to oppose mass flow, and their velocities were reduced accordingly (Fig. 24). The increased average velocity of currents at 18 m of depth was due to density underflows being pulled toward the dam by bottom discharge.

TABLE XXI

AVERAGE CURRENT VELOCITIES AND PRECISION OF THE FREE DRAG METHOD IN KEYSTONE RESERVOIR

Meters of Depth	Number of Observations	$m\ min^{-1}$ $\bar{X} \pm S$	Coefficient of Variation (%)
0	80	5.10 ± 0.58	11.4
5	47	2.82 ± 0.51	18.1
10	46	1.70 ± 0.35	20.6
14	17	1.65 ± 0.22	13.3
18	21	3.84 ± 0.54	14.1
		$\bar{\bar{X}} \pm \bar{S} = 3.02 \pm 0.44$	14.6

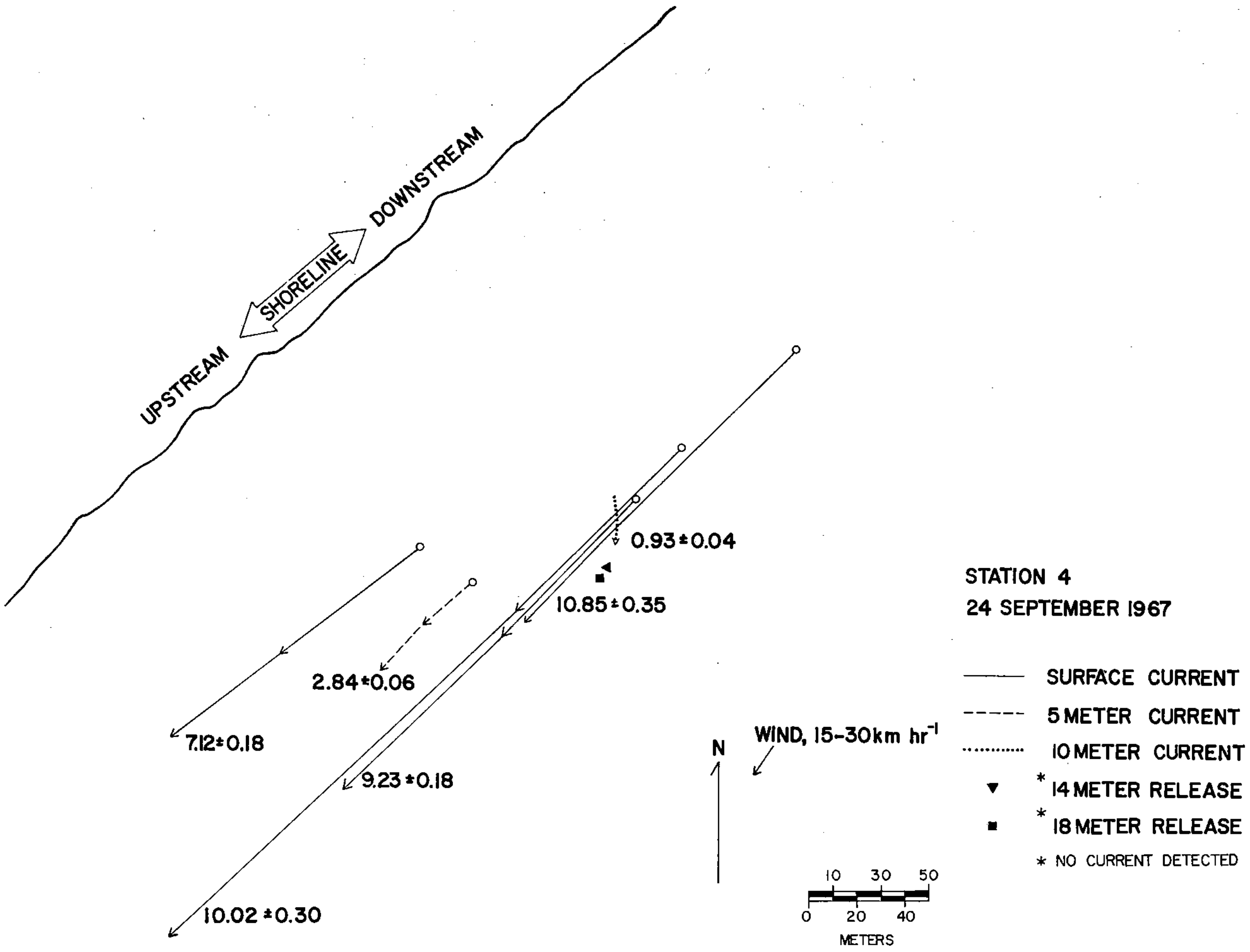

Figure 25. Speed (m min^{-1}) and direction of surface and sub-surface currents at Station IV, 24 September 1967

Velocities of currents at various depths in Keystone Reservoir (Table XXI) are similar to the velocities of currents in Lake Mendota (Table XXII). The velocity of the underflowing density current of Keystone Reservoir is within the range of velocities reported for similar underflows in other reservoirs.

Direction of Currents

At Station III on several occasions during 1967, a boat tied to a permanent buoy oriented itself upstream into the wind, indicating an upstream mass flow caused by something other than wind action. In August 1967, the speed and direction of surface and sub-surface currents were measured at Station III using the free-drag method (Fig. 26). Wind was from the northeast at variable speeds from 5 to 25 km hr^{-1}. When wind velocities were between 5 and 10 km hr^{-1}, an upstream surface current of 2.66 m min^{-1} existed against the wind. Increases in wind velocities to 15 to 25 km hr^{-1} were sufficient to offset the upstream mass flow and produced a cross-wind surface current of approximately 1.85 m min^{-1}. Even high wind velocities were not sufficient to prevent upstream flow at 5 m of depth, but the direction was slightly altered to a cross-wind course (Fig. 26). A downstream mass flow occurred in the lower layers with velocities ranging from 3.60 m min^{-1} at 10 m to 4.77 m min^{-1} at 14 m. The relatively low velocities of currents at 5 m indicate that upstream mass flow did not greatly exceed 5 m of depth and that currents at 5 m were close to the shearing plane between the two opposing mass flows.

On 22-23 June 1968, a complete survey of the direction and velocity of surface and sub-surface currents in Keystone Reservoir was made

TABLE XXII

COMPARISON OF THE VELOCITY OF CURRENTS IN LAKES AND RESERVOIRS

Water Body	Reference	Type of Currents	Depth (m)	Type of Data	Current Velocity (m min^{-1})
Lake Mendota, Wisconsin	Lathbury et al. (1960)	wind driven or seiche	0	10 yr $\bar{X}$	5.6
			5	"	1.9
		"	10	"	1.7
		"	15	"	1.0
		density flows	18	"	4.6
Loch Garry, Scotland	Wedderburn (1908)	wind driven	0		16.8
		cyclonic swirl	61		1.9
Lake Constance, Switzerland	Elster (1939)	wind driven	0	$\bar{X}$	9.8
		cyclonic swirl	50		0.0
Sweetwater Lake, California	Ramsey (1960)	wind driven	0	min-max	1.5-3.0
Crater Lake, Oregon	Kibby et al. (1968)	wind driven	0	max	6.2
TVA reservoirs	Fry et al. (1953)	density flows		min-max	2.7-6.4
Senegari Reservoir, Japan	Goda (1959)	density flows		max	3
Lake Mead, Arizona	A.S.C.E. (1963), from data of Smith et al. (1960)	density underflows			6.4

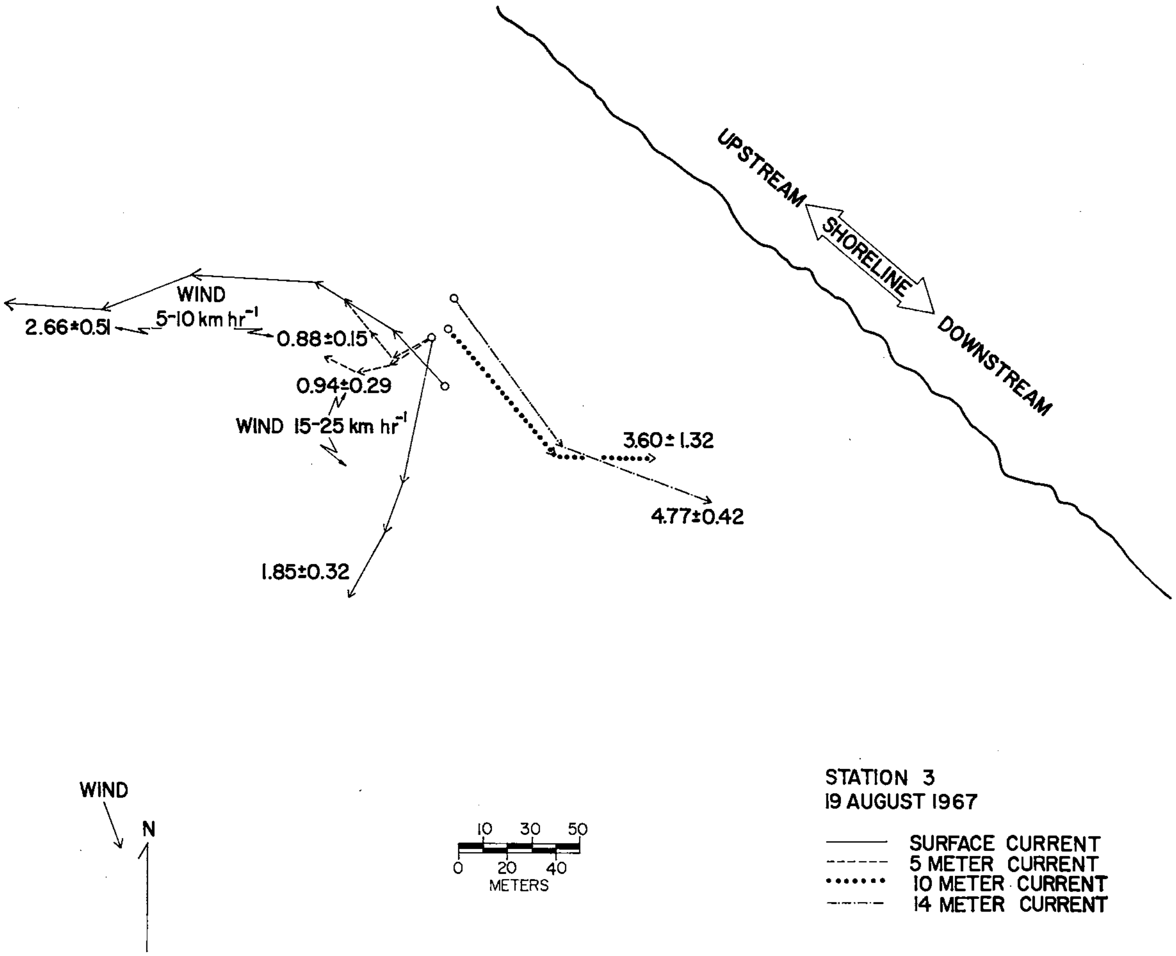

Figure 26. Speed (m min^{-1}) and direction of surface and sub-surface currents at Station III, 19 August 1967

(Fig. 27). Greatest velocities were present at the inflow of the Arkansas and Cimarron Rivers, in surface waters when wind driven currents were in the direction of mass flow, and in a downstream density current along the bottom of the Cimarron arm. Lowest current velocities were recorded in an upstream flow along the bottom of the Arkansas arm. Observations made at the surface and 5 m of depth approximately 5 km upstream in the Cimarron arm offer further evidence that wind velocities occasionally were sufficient to cause surface currents to flow in the direction of prevailing wind (Fig. 27). Occasionally, wind action was sufficient to cause surface currents to directly oppose a mass flow of considerable velocity, as shown by observations 5 km above the dam in the Arkansas arm (Fig. 27). At that point an upstream wind driven surface current of 2.9 m min^{-1} was present, although a downstream wind-aided mass flow of 5.1 m min^{-1} existed only 7 km upstream (Fig. 27).

Further verification of the upstream flow in the surface waters of the Cimarron arm was shown by the direction of currents on 7 July 1968 (Table XXIII). An upstream mass flow of varying velocity existed throughout the day between 0 and 5 m depth, and a downstream mass flow existed throughout the day below 12 m of depth. The randomness of direction and low velocity of currents at 8 m of depth indicated the location of the shearing plane between opposing mass flows. Surface flows moving upstream to offset downstream bottom flows also have been observed in Fort Patrick Henry Reservoir by Churchill (1957) and in Slapy Reservoir by Hrbacek and Straskraba (1966).

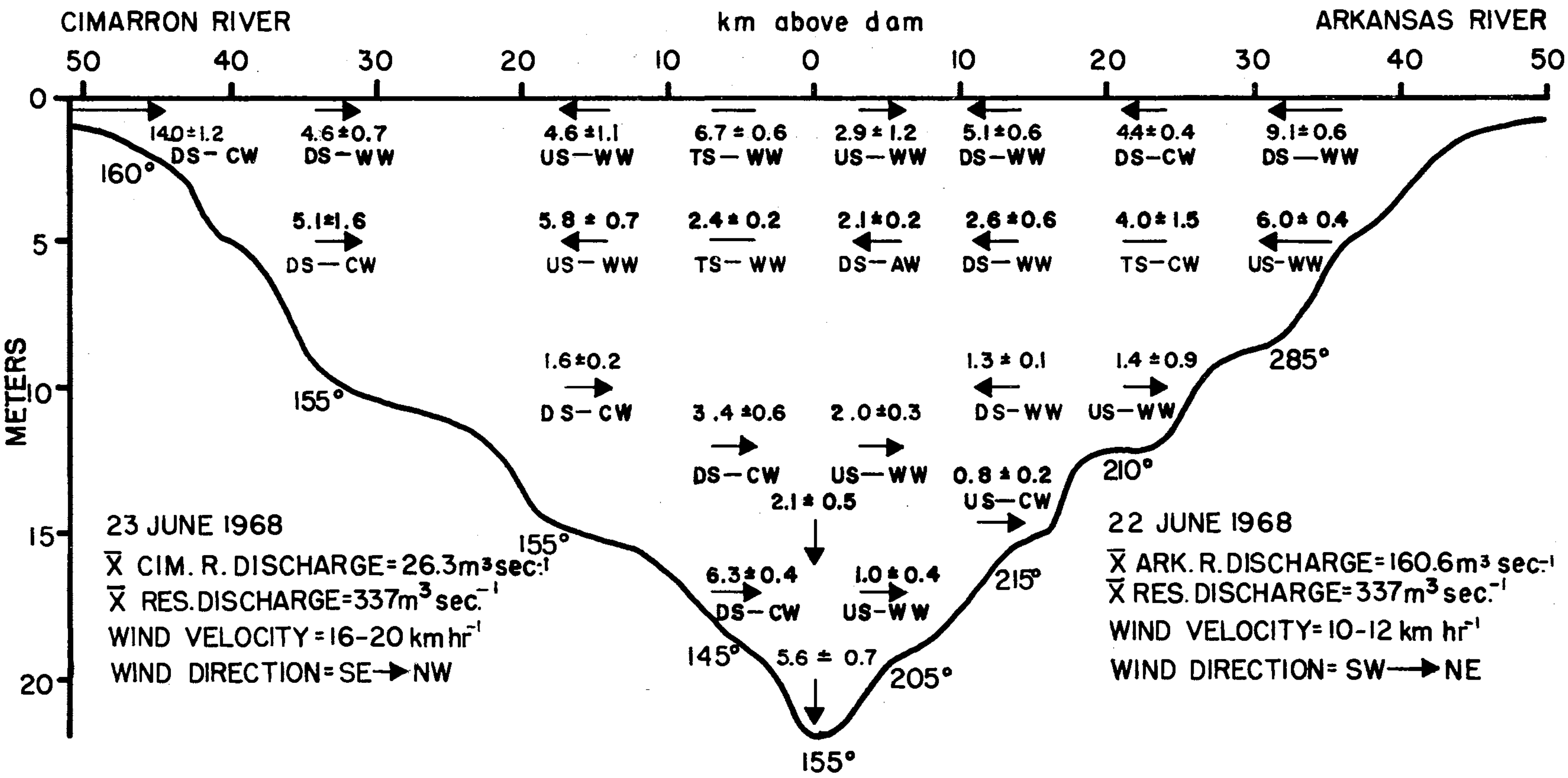

Figure 27. Speed ($\bar{X} \pm S$ m min^{-1} of three observations) and direction of currents in Keystone Reservoir on 22-23 June 1968. DS = downstream, US = upstream, TS = toward shore, WW = with wind, AW = against wind, and CW = across wind. Numbers below bottom profile are the average degrees from true North from which wind was blowing during measurements at that location.

TABLE XXIII

VARIATION IN SPEED AND DIRECTION OF CURRENTS AT STATION IV, 7 JULY 1968*

	Time of Day (hr)		
	9.80 - 10.15	13.50 - 14.00	17.50 - 18.00
Wind (km hr^{-1})	0-1 S-SE	0-1 variable	2-3 E-NE
Surface (m min^{-1})	0.77 ± 0.58 toward shore	1.32 ± 0.36 upstream	2.79 ± 0.49 upstream
4 m	1.44 ± 0.18 upstream	0.99 ± 0.12 upstream	0.47 ± 0.12 upstream
8 m	0.46 ± 0.14 toward shore	0.56 ± 0.16 circle	0.75 ± 0.12 toward shore
12 m	1.73 ± 0.15 downstream	1.34 ± 0.14 downstream	1.32 ± 0.10 downstream
16 m	2.02 ± 0.35 downstream	2.70 ± 0.56 downstream	1.59 ± 0.26 downstream

*Derived from measurements made by K. A. Kochsiek.

Circulation Patterns

Two distinct circulation patterns existed in Keystone Reservoir during 1965-67, depending on the method of reservoir operation (Fig. 28). These patterns of circulation were suggested by isolines of conductivity (Fig. 21) and the distribution of Cl/SO$_4$ ratios (Fig. 22) and were verified by direct measurements of the direction of surface and sub-surface currents (Fig. 27).

During 1965-66 when all reservoir discharges were from surface waters, the Cimarron River entered Keystone Reservoir as an underflow

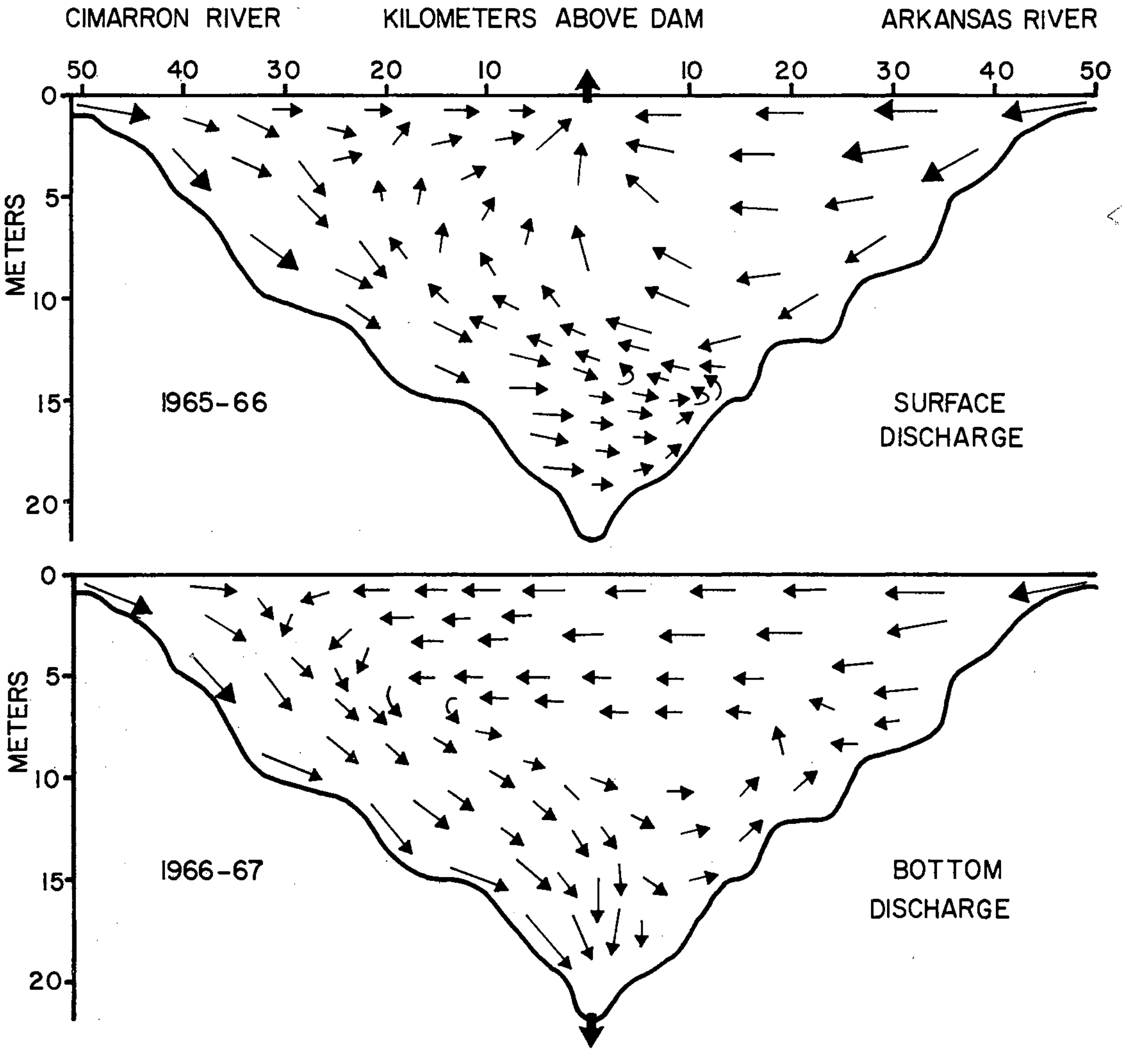

Figure 28. Effects of the level of reservoir discharge on circulation patterns in Keystone Reservoir. Relative speed of flows, which was derived from current measurements, is indicated by the size of arrows. General direction of flows was derived from current measurements, isolines of conductivity, and distribution of Cl/SO_4 ratios. Direction of flows above 5 m of depth often was modified by wind action.

during dry periods and as an interflow during wet periods. Highly mineralized water flowed along the bottom of the Cimarron arm and collected above the dam forming partial meromixis. Dense Cimarron water which built up in volume above the dam flowed up the bottom of the Arkansas arm for a distance of approximately 15 km. The Arkansas River entered the reservoir and flowed at all depths through the Arkansas arm until reaching the build-up of dense Cimarron water backed up in the Arkansas arm. At this point, Arkansas River water formed an overflow over denser water of Cimarron River origin and traveled for approximately 20 km up the Cimarron arm before turning back as a downstream surface flow toward the dam. The majority of water released from Keystone Reservoir during 1965-66 was a direct overflow of water from the Arkansas River moving along the surface of the Arkansas arm. A mixolimnion of both Arkansas and Cimarron water was present in the lower half of the Cimarron arm. The observed pattern of circulation during 1965-66 was similar to a hypothetical flow pattern generated by a mass transfer model (Falls 1969).

During 1966-67, the change in level of reservoir discharge from the epilimnion to the hypolimnion produced a striking difference in the pattern of circulation in Keystone Reservoir (Fig. 28). Dense water from the Cimarron River again formed an underflow along the bottom of the Cimarron arm, but instead of building up above the dam, the underflow was released through sluice gates. Less mineralized Arkansas River water entered the reservoir and formed an overflow down the Arkansas arm and up the Cimarron arm for approximately 30 km above the dam before turning and flowing back through the Cimarron arm as a downstream interflow. The underflow of Cimarron water combined with the interflow of Arkansas water and produced a downstream mass flow through the lower half of the Cimarron arm greater than the volume being discharged. The excess volume primarily of Arkansas River origin, but containing some water of Cimarron origin because of mixing occurring in the Cimarron arm, formed an upstream underflow up the Arkansas arm for a distance of at least 20 km above the dam. This upstream underflow in the Arkansas arm was verified by direct current measurements on 22 June 1968 (Fig. 27). The upstream underflow was detected approximately 6 km above the dam at 12 and 17 m of depth, approximately 15 km above the dam at 14 m of depth, and approximately 24 km above the dam at 10 m of depth. The average velocity of 12 observations made in three locations in the upstream underflow in the Arkansas arm was 1.3 ± 0.4 m min^{-1}. The observed pattern of circulation in Keystone Reservoir during 1966-67 is in disagreement with the hypothetical flow pattern generated by a mass transfer model (Falls 1969). Falls (1969) suggested,

> When water is released from the bottom layers of the reservoir, . . . lighter Arkansas water . . . will exhibit its strongest flow in the lower half of the Arkansas arm, flowing toward the outlet gate. Lighter flows are expected in the upper layers.

Current velocities in the upstream underflow of the Arkansas arm were among the lowest recorded in the reservoir. The greatest current velocities were recorded in the downstream overflow of the Arkansas arm, in the upstream surface flow of the Cimarron arm, and in the downstream underflow of the Cimarron (Fig. 27).

An accurate estimate of the retention time of a reservoir is important in predicting the effects of polluted inflows on water quality in the reservoir or in predicting the water quality of reservoir discharge. The retention time of a reservoir theoretically can be computed by dividing volume by total inflow. This theoretical value has little practical use since its calculation is based on assumptions that the density of inflow is equal to the reservoir density, no stratification exists in the reservoir, and water is released from the reservoir from all depths. Using data for Keystone Reservoir presented in Tables I and III, the theoretical retention time would be 20.1 days for the Cimarron arm, 8.9 days for the Arkansas arm, or average 9.5 days for the entire reservoir. Theoretical retention times given in the literature for other water bodies are 38.5 days for Slapy Reservoir (Hrbacek and Straskraba 1966); 11, 12 and 14 days for three TVA reservoirs (Churchill and Nicholas 1967); and about four years for Lake Mendota (Rohlich 1963) and Lake Constance (Lanzer 1961).

Since the assumptions of theoretical retention time were not met in Keystone Reservoir, an attempt to estimate true retention time using current measurements and circulation patterns was made. Assuming the circulation pattern presented in Fig. 28 for 1966-67 and the physicochemical conditions and current velocities present in the reservoir on 22-23 June 1968, the time of travel of various water masses in Keystone Reservoir was calculated (Fig. 29). Using the time of travel estimates presented in Fig. 29, the estimated retention time of the downstream underflow of Cimarron River water would be approximately 6 days. The Arkansas River water which traveled as an overflow down the Arkansas arm and up the Cimarron arm and then traveled back down the Cimarron arm as an interflow to the dam would have a retention time of approximately 18 days. Water from this interflow which was not released from the dam and which traveled back up the Arkansas arm as an underflow and then traveled back down the Arkansas arm and up the Cimarron arm as an

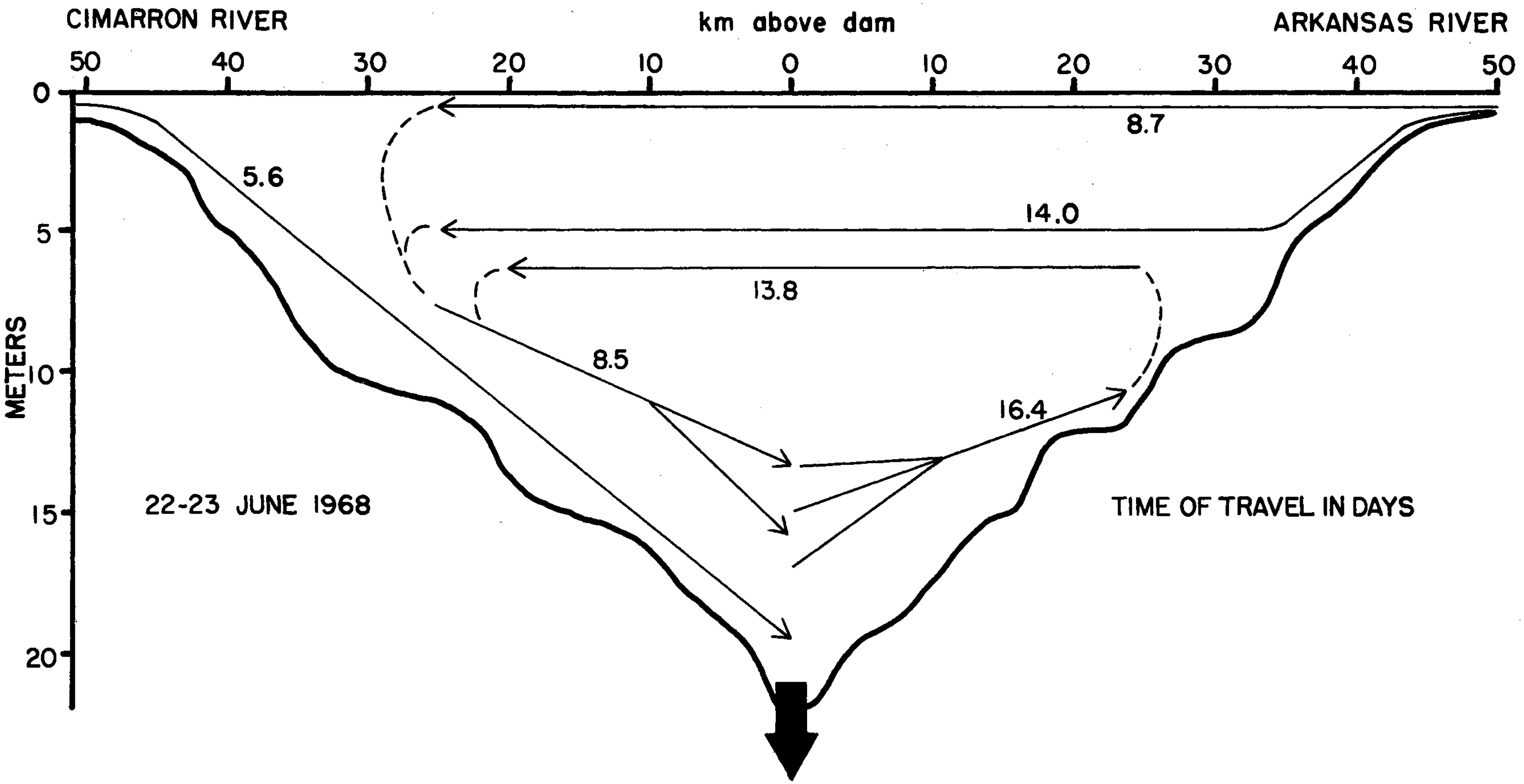

Figure 29. Estimated time of travel (days) of water masses in Keystone Reservoir assuming the physicochemical conditions present on 22-23 June 1968

interflow and then traveled back down the Cimarron arm to the dam would have a retention time of approximately 48 days. These estimated times probably should be considered as minimum retention times, but variations in quantity or density of inflows, quantity of reservoir discharge, intensity of reservoir stratification, and wind velocity and direction could interact to produce increases or decreases in actual retention times.

Effects of Impoundment on Water Quality

The major effects of impoundment on water quality of inflowing rivers are well known and have been reviewed by Churchill (1957), Kittrell (1959), and Churchill and Nicholas (1967). Changes most often observed between inflows and outflows of impoundments are decreases in temperature, dissolved oxygen, pH, and turbidity and increases in CO_2, H_2S, and NH_3.

Keystone Reservoir had a notable effect on the water quality of the Cimarron River during 1965-67, with the magnitude of change depending on the level of reservoir discharge (Fig. 30). Physicochemical conditions of Cimarron River inflows were measured at Station I. Physicochemical conditions of outflows were measured at Station IV at the depth from which water was being released through the dam. The most striking effects of impoundment on the water quality of the Cimarron River were large reductions in conductivity and turbidity. Temperatures of reservoir outflow exceeded inflow temperatures during the winter months but were less than inflow temperatures during the summer months. Dissolved oxygen concentration of reservoir outflow always was less than that of Cimarron River inflow, except between April and July

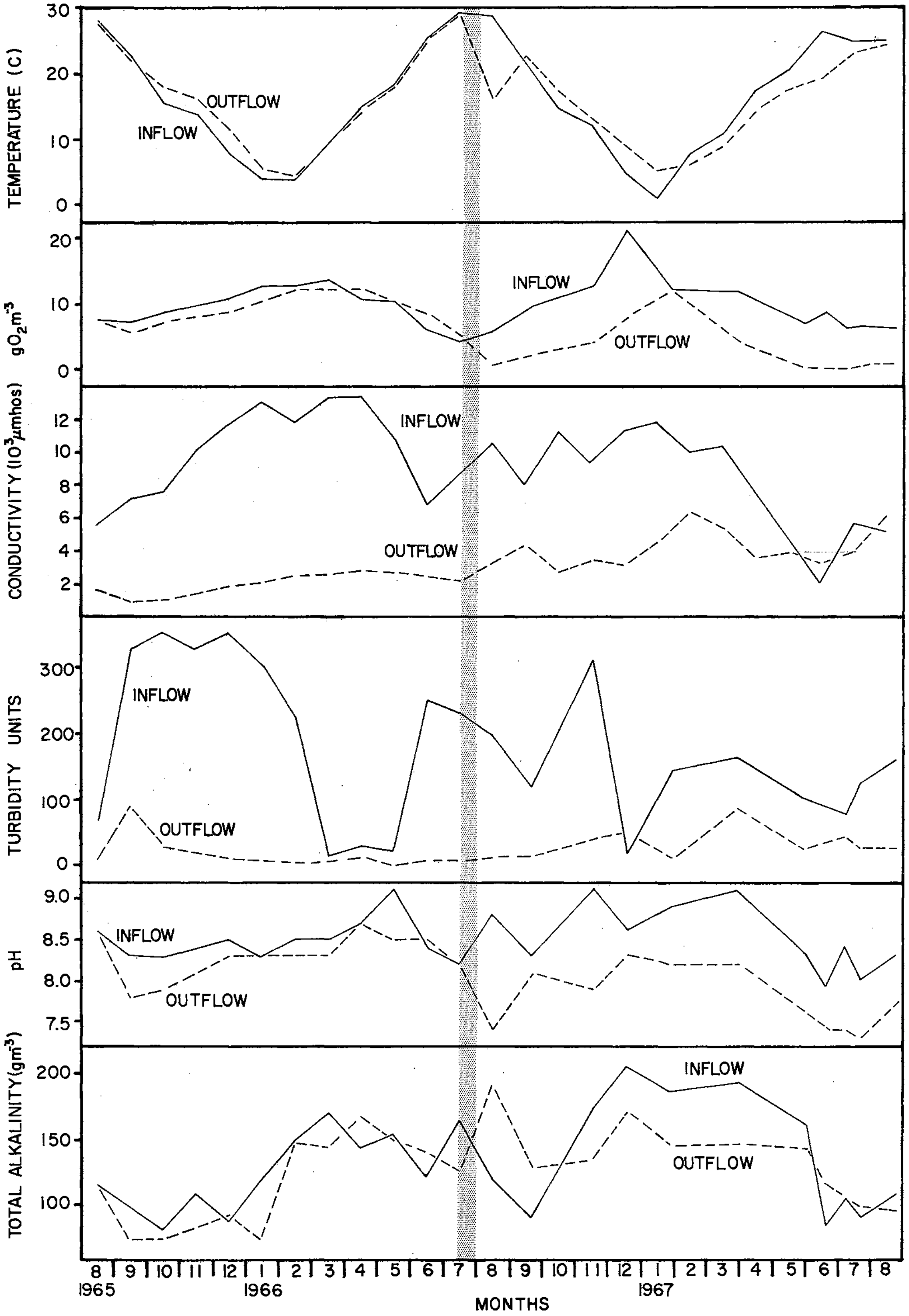

Figure 30. Effects of impoundment on water quality of the Cimarron River. Shaded area indicates the period of time during which the level of discharge was being changed from the epilimnion to the hypolimnion.

1966 when high primary productivity in the euphotic zone of the reservoir apparently supersaturated surface water with oxygen and caused oxygen concentrations in water released through tainter gates to exceed concentrations in the inflowing Cimarron River. Alkalinity and pH of Cimarron inflows exceeded alkalinity and pH of reservoir outflows throughout most of 1965-67.

Although the change in reservoir discharge level between 1965-66 and 1966-67 produced an improvement in the quality of water in Keystone Reservoir, the change was detrimental to the quality of reservoir discharge (Table XXIV). The change from epilimnetic discharge to hypolimnetic discharge decreased the effectiveness of the reservoir in reducing conductivity from 78% to 48% and in reducing turbidity from 92% to 74% and resulted in an increase in the reduction of dissolved oxygen concentration from 10% to 68%. Change in level of reservoir discharge also increased the reduction of temperature, alkalinity, and pH, but these changes were not as significant in altering the quality of reservoir discharge as were the changes in the effect of impoundment on conductivity, turbidity, and dissolved oxygen.

Solids and Sedimentation

Solids contained in reservoir waters may be classified as either dissolved or suspended. Dissolved solids provide an estimate of the concentration of inorganic ions or the degree of "mineralization" of water. Concentrations of dissolved solids may be estimated directly by gravimetric analysis of filtered water samples or indirectly by conductivity measurements. Suspended solids include sand, clays, silt, and plankton and provide an estimate of potential sediment. Suspended

TABLE XXIV

RELATION OF THE EFFECT OF IMPOUNDMENT ON WATER QUALITY TO RESERVOIR DISCHARGE LEVEL

Water Year	Level of Reservoir Discharge	Annual Mean Reduction (%) Between Inflow and Outflow					
		Temperature	Conductivity	Turbidity	Alkalinity	pH	Dissolved Oxygen
1965-66	epilimnion	2	78	92	3	4	10
1966-67	hypolimnion	4	48	74	7	8	68

solids may be estimated directly from the difference between gravimetric analyses of filtered and unfiltered water samples, or indirectly by photometric turbidity measurements.

Concentrations (g m^{-3}) of dissolved and suspended solids in the Cimarron arm generally decreased between Stations I and IV, while amounts (g m^{-2}) increased (Table XXV). Concentrations of dissolved solids increased with depth. Concentrations of suspended solids were higher in the density current flowing along the bottom of the Cimarron arm, while no significant changes occurred with depth in the upper waters, except for an increase in the surface waters of Station III. The increase in the annual mean concentration of suspended solids in the surface waters of Station III primarily was due to the high concentration (220 g m^{-3}) of suspended solids present in March 1967. Chlorophyll analyses during March 1967 indicated that this high concentration of suspended solids was not due to a phytoplankton bloom. Zooplankton samples were not collected; therefore, speculation about their contribution to the suspended solids in March 1967 cannot be made, although low concentrations of astacin type carotenoids indicated that Crustacea were not particularly abundant (Spangler 1969).

Concentrations (g m^{-3}) of chloride ion on the average were equivalent to 32% of the concentration of total dissolved solids and were equivalent to 24% of the μmhos of specific conductance (Table XXV). Concentrations (g m^{-3}) of dissolved solids on the average were equivalent to 75% of the μmhos of specific conductance. Concentrations (g m^{-3}) of dissolved solids in Lake Mead averaged about 70% of the μmhos of specific conductance (Smith et al. 1960).

TABLE XXV

ANNUAL MEANS OF CONCENTRATIONS (g m^{-3}) AND AMOUNTS (g m^{-2}) OF SOLIDS AND CONCENTRATIONS OF CHLORIDE ION AND TURBIDITY IN KEYSTONE RESERVOIR DURING 1966-67

Depth (m)	Stations													
	I		II		III		IV	I		II		III		IV
1	6390	*	1670		1413		1302	160	*	26	*	40	*	16
5			1719	*	1444		1300			21		20		14
			*							*				
10			2196	*	1516		1319			86	*	18		16
					*		*					*		
14	Dissolved Solids				2220		2197	Suspended Solids				36	*	21
														*
18							2352							77
g m^{-2}	7893	*	14496	*	21732	*	29020	209	*	355		366		424
1	1322	*	653	*	585	*	516	143	*	26	*	35	*	19
												*		
5			651	*	590	*	518			27		18		21
			*							*				
10			834	*	631	*	530			75	*	18		21
					*		*					*		
14	Chloride Ion				746	*	592	Turbidity Units				38	*	20
							*							*
18							739							69

* indicates significant difference ($\alpha = 0.10$) between means using depth x date MS as error term to test for differences among depths within stations and station x date MS to test for differences among stations within depths.

The relationship between photometric measurements of turbidity and concentrations of suspended solids apparently depended on the optical properties of solids present. Gravimetric estimates of suspended solids exceeded turbidity measurements during 7 months of 1966-67, while turbidity exceeded gravimetric estimates during 5 months (Fig. 31). Averaged over all measurements, turbidity units were equivalent to 96% of the concentration (g m^{-3}) of suspended solids. The 4% difference was considerably less than the coefficient of variation for the gravimetric method of analysis, and turbidity units were considered to be as good an estimate of suspended solids as gravimetric estimates.

Annual mean turbidity for 1965-66 was higher than the annual mean for 1966-67 (Table XVI). The higher annual mean during 1965-66 was due to high concentrations of suspended solids during the fall of 1965 (Fig. 31). Turbidity was lower from January through August in 1966 than in 1967. A large increase in the suspended solids content of the Cimarron arm in July 1967 was caused by a flood which occurred during the last half of June.

An indirect estimate of the rate of sedimentation in the Cimarron arm during 1965-66 and 1966-67 was made, assuming turbidity units were equivalent to g m^{-3} suspended solids (Table XXVI). The weight of suspended solids deposited as sediment was converted to volume assuming a weight-volume relationship of 1.30 metric tons of unpacked, dry sediment per m^3. This relationship was derived from data for Lake Mead, Arizona, in which sediment averages about 45% sand and 55% silt and clay (Smith et al. 1960). Estimates of the amount of sediment in Lake Mead made by mass-balance calculations assuming a weight-volume relationship of 1.30 metric tons m^{-3} were within 2% of more direct

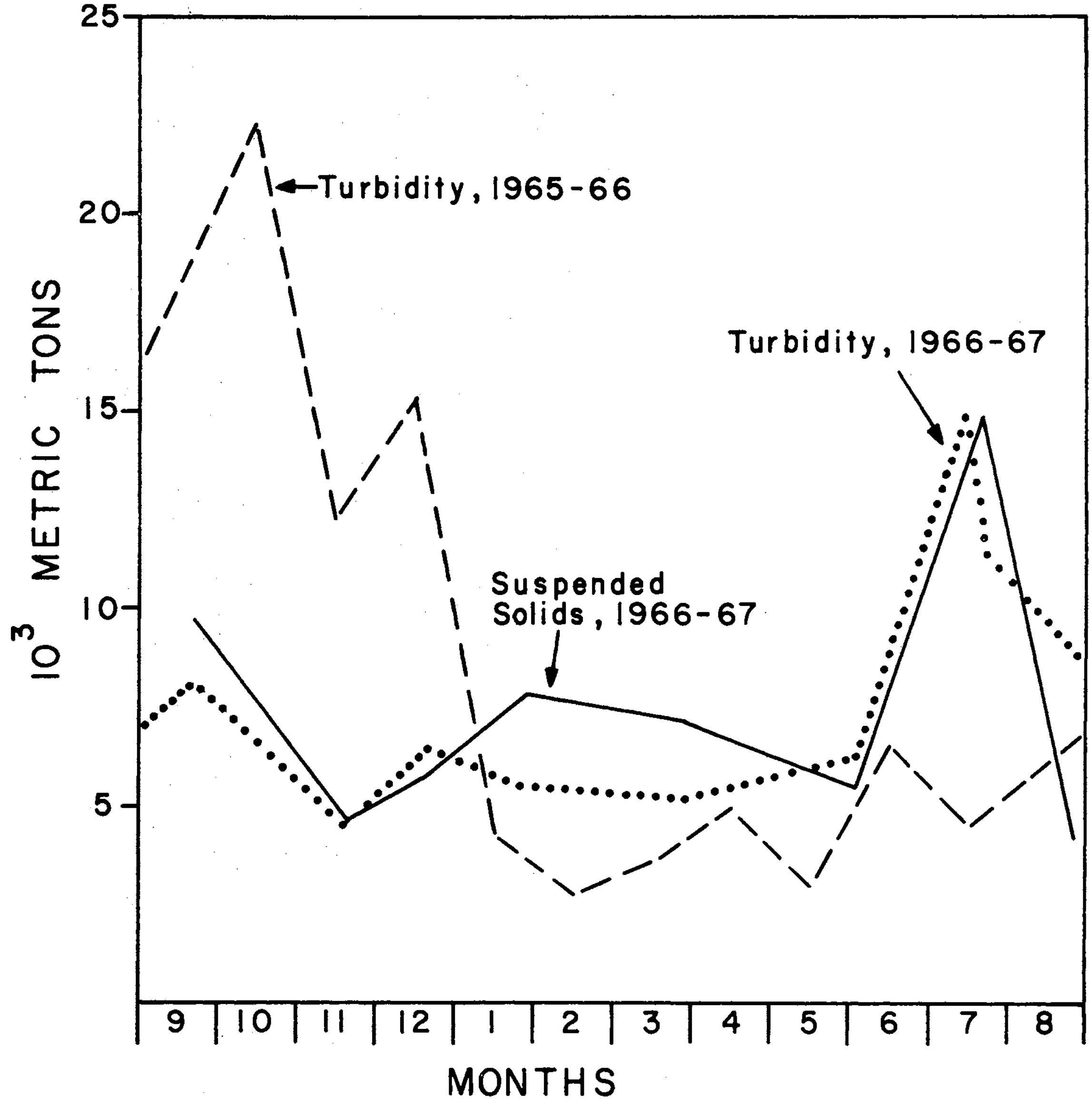

Figure 31. Comparison of turbidity and suspended solids content of the Cimarron arm during 1965-66 and 1966-67

TABLE XXVI

BALANCE OF SUSPENDED SOLIDS IN CIMARRON ARM DURING 1965-66 AND 1966-67 INDICATING RATE OF SEDIMENTATION

(All Amounts Except Volumes Are 10^3 Metric Tons)

	1965-66	1966-67	$\bar{X}$
Total inflow	382.7	43.1	212.9
Total outflow	43.9	13.4	28.7
Amount retained	338.8	29.7	184.2
Solids suspended in water at beginning of water year	16.1	6.9	11.5
Solids suspended in water at end of water year	6.9	9.0	8.0
Change in content during water year	-9.2	+2.1	-3.5
Weight of solids lost to sediments	348.0	27.6	187.7
Volume* (10^3 m^3 of solids lost to sediments	267.4	21.2	144.3

*Calculated assuming a weight-volume relationship of 1.30 metric tons of unpacked, dry sediment per m^3 derived from data presented by Smith et al. (1960).

estimates made from echo soundings during hydrographic surveys (Smith et al. 1960). Variations in particle size and proportions of sand and clays composing the sediments of Lake Mead and Keystone Reservoir probably resulted in errors in estimating sediment volume of Keystone. Estimates of the outflows of suspended solids from Keystone Reservoir probably are valid, but estimates of the inflow of suspended solids into the Cimarron arm probably underestimated the actual sediment load of the Cimarron River. The total inflow of suspended solids was estimated by multiplying monthly estimates of the concentration of suspended solids at Station I by total monthly Cimarron River discharge and summing the products. Samples used to estimate the concentration of suspended solids at Station I were always collected at least 0.5 m above the river bottom and on some occasions probably underestimated the average concentration of suspended solids in the water mass.

The estimated total inflow of suspended solids into the Cimarron arm during 1965-66 was 9.1 times the total inflow during 1966-67 (Table XXVI), while the annual Cimarron River discharge during 1965-66 was only 1.3 times the annual discharge of 1966-67 (Table III). Sediment load is not directly proportional to run-off but increases more rapidly with increasing discharge (Smith et al. 1960). Between 1926 and 1949 the annual suspended load of the Colorado River at Grand Canyon varied from 45 metric tons in 1934, when runoff was less than 6.2×10^9 m^3, to nearly 454 metric tons in 1929, when annual runoff was more than 23.4×10^9 m^3 (Smith et al. 1960). The large annual variation in the suspended load of the Cimarron and Colorado Rivers indicated that estimates of the rate of sedimentation used to predict the life expectancy of reservoirs should be based on long-term, intensive sampling programs.

Assuming that 144.3 x 10^3 m^3 is a valid estimate of the long-term rate of sedimentation, the Cimarron arm of Keystone Reservoir would have a life expectancy of about 20 centuries before sediments fill the reservoir to normal power pool level. Based on the rate of sediment accumulation during the first 14 years of impoundment, it will be slightly less than 5 centuries before Lake Mead is filled with sediment to the level of the permanent spillway crest (Smith et al. 1960). A long-term, more intensive study of the rate of sedimentation in Keystone Reservoir probably would show that the life expectancy is considerably less than 20 centuries.

Heat Budgets

Heat budgets have long been used by limnologists to classify lakes according to their thermal properties. The first work with heat budgets was done by Forel (1880). Forel's methods apparently were theoretically unsound and the revised methods and definitions of Birge (1915) have been accepted as standard methods for calculating heat budgets. The annual heat budget of a lake may be defined as the total amount of heat that enters the lake between the time of its lowest and its highest heat content (Hutchinson 1957). This quantity may be sub-divided for temperate dimictic lakes into summer and winter heat budgets. The summer heat budget may be defined as the amount of heat required to raise a lake from an isothermal condition at 4 C up to the highest observed summer heat content, with most of the distribution of heat being accomplished by wind action. The winter heat budget may be defined as the amount of heat needed to raise the water of a lake from the temperature at time of minimum heat content up to 4 C, with most of the heat distribution being accomplished by convection streaming. In warm monomictic lakes with minimum heat contents above 4 C, the winter heat budget is calculated by the difference between the minimum heat content of the lake and the theoretical heat content at an isothermal temperature of 4 C. This quantity may be considered as the negative winter heat income and is a measure of the equatorial versus temperate nature of lakes (Hutchinson 1957).

To determine the heat budget of Keystone Reservoir, the volume-weighted mean temperature of the reservoir was determined for each month of 1965-67, and the times of minimum and maximum heat content were selected. Minimum and maximum heat contents were calculated from average temperature profiles (Fig. 32), by plotting depth z against the product of $(A_z)(T_z)$, where A_z equals the area at depth z and T_z equals the average temperature at depth z; integrating the area under the resulting curve; and dividing by the surface area of the reservoir. The heat content of Keystone Reservoir varied from a maximum of 21,289 cal cm^{-2} in August 1965 to a minimum of 3,451 cal cm^{-2} in January 1967 (Fig. 33). Average water temperatures and average and extreme air temperatures at times of minimum and maximum heat contents are shown in Table XXVII. The average annual heat budget of Keystone Reservoir was 17,217 cal cm^{-2}, and the reservoir had an average negative winter heat income of -995 cal cm^{-2}. The temperate nature of monomictic Keystone Reservoir is demonstrated by comparing the negative winter heat income of Keystone to that of Lake Atitlan, Guatemala. Atitlan has an annual heat budget of 22,110 cal cm^{-2}, similar in magnitude to the annual heat budget of Keystone Reservoir, but has a negative winter heat income of -288,300 cal cm^{-2}.

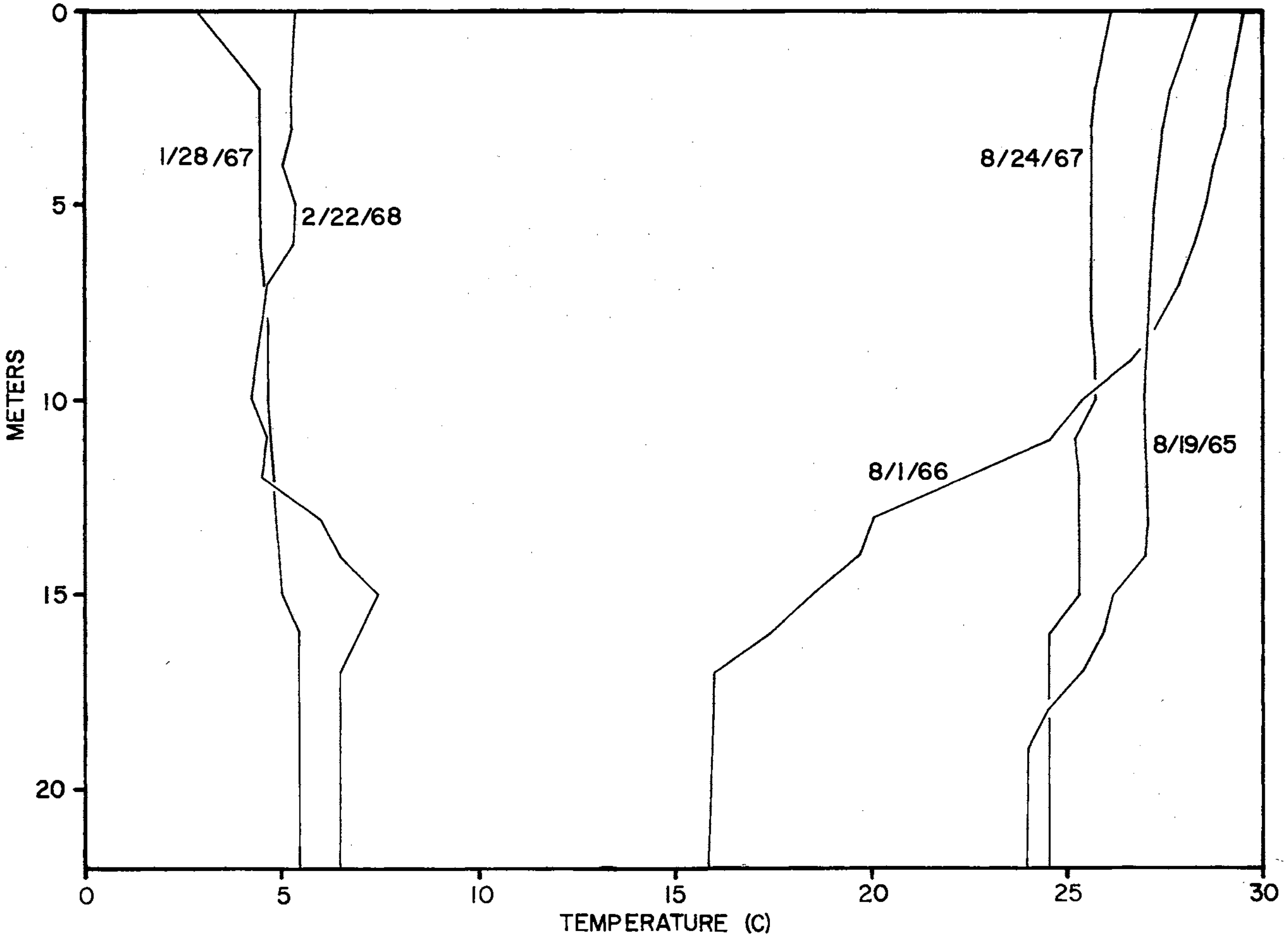

Figure 32. Average temperature profiles on dates of minimum and maximum heat content of Keystone Reservoir

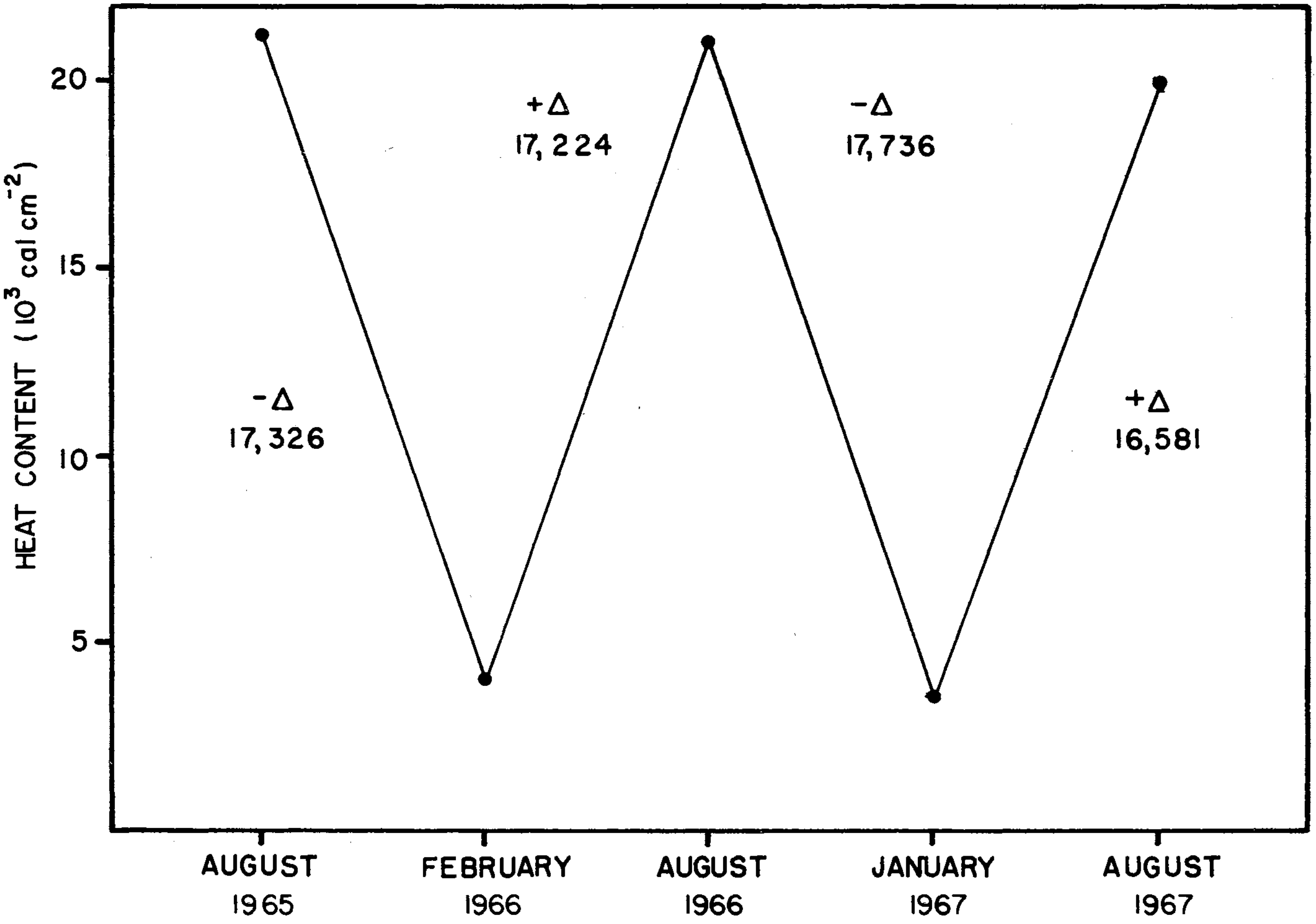

Figure 33. Minimum and maximum heat contents and Birgean heat budgets for Keystone Reservoir

TABLE XXVII

AVERAGE AIR[*] AND WATER TEMPERATURES AT TIMES OF MINIMUM AND MAXIMUM HEAT CONTENT OF KEYSTONE RESERVOIR

Date	$\bar{X}$ Water Temp. C	$\bar{X}$ Air Temp. C	Max. or Min. Monthly $\bar{X}$ Air Temp. of Season (C)
August 1965	26.7	27.6	27.6 in August
February 1966	5.4	3.9	0.4 in January
August 1966	23.8	25.8	30.7 in July
January 1967	4.7	4.2	2.9 in December
August 1967	25.3	24.4	25.3 in July

[*] Air temperatures were derived from records of U. S. Weather Bureau for Tulsa, Oklahoma.

Keystone Reservoir would be classified thermally as a second-class lake according to the scheme of classification of Birge (1915). Birge considered a first-class lake in temperate North America to be any body of water with a surface area of at least 20 km^2 and a mean depth of at least 30 m. Lakes with these dimensions were assumed to take up the climatic maximum amount of heat. Shallower lakes were considered to be unable to take up the maximum amount of heat and were classified as secondary.

A more recent analysis of the relationship between lake morphometry and heat budgets in 43 dimictic and 28 warm monomictic lakes in the temperate zone indicated that heat budgets continue to increase as mean depth becomes greater than 30 m or surface area exceeds 20 km^2

(Gorham 1964). Gorham (1964) found a high correlation between annual heat budgets of temperate lakes and their mean depth ($\bar{Z}$ in m), surface area (A in m^2), and volume (V in m^3). The accuracy of the regression equations which Gorham (1964) derived to estimate heat budgets was tested by estimating the annual heat budget of Keystone Reservoir from morphometric data given in Table I (Table XXVIII). The three estimates deviated significantly from the observed heat budget, but the average of the estimates (19,026 cal cm^{-2} yr^{-1}) was reasonably close to the observed value.

TABLE XXVIII

COMPARISON OF THE AVERAGE OBSERVED ANNUAL HEAT BUDGET OF KEYSTONE RESERVOIR TO HEAT BUDGETS ESTIMATED FROM MORPHOMETRY USING THE EQUATIONS OF GORHAM (1964)

Equation	Value of Unknown for Keystone	Heat Budget cal cm^{-2} yr^{-1}
$\Theta_{ba} = 18.4 \log_{10} \bar{Z} - 2.52$	$\bar{Z} = 7.7$	13,790
$\Theta_{ba} = 14.8 \log_{10} \sqrt{A} - 28.3$	$\sqrt{A} = 10320$	31,100
$\Theta_{ba} = 18.8 \log_{10} \sqrt[3]{V} - 29.7$	$\sqrt[3]{V} = 169.1$	12,189
	Average Observed Heat Budget	17,217

No corrections were made for heat lost to sediments in calculating the annual heat budget of Keystone Reservoir; therefore, values must be considered as the heat budget of both water and sediments. In Lake Mendota, which has an annual heat budget (23,500 cal cm^{-2}) similar to that of Keystone Reservoir, 1,350 cal cm^{-2} were lost to sediments (Birge 1916). In shallower, monomictic Keystone Reservoir, the loss to sediments may be even more important than in Lake Mendota.

All sources of heat gains and losses from the reservoir were not determined, but gains and losses of heat due to differences in heat content of inflowing and outflowing water during 1965-67 were determined (Fig. 34). The change in level of reservoir discharge appeared to have a definite effect on the pattern of net gains and losses of heat due to differences in heat content of inflows and outflows. During 1965-66 when all releases were from the epilimnion, the reservoir showed a net heat gain between inflows and outflows during all months except November, December, January, and February. During 1966-67 with hypolimnetic discharge, the reservoir showed a net heat loss between inflows and outflows during 7 months of the year, but the gains occurring during the spring and summer months were sufficient to result in an increase in the annual net gain of heat. During 1965-66, inflows into Keystone Reservoir had a total heat content of 61.07 x 10^9 cal, and outflows had a heat content of 57.97 x 10^9 cal, resulting in a net heat gain of 3.10 x 10^9 cal. During 1966-67, inflows had a higher heat content (63.42 x 10^9 cal) than in 1965-66, but outflows had a total heat content of only 55.91 x 10^9 cal, resulting in an increased net gain of 7.51 x 10^9 cal. The fact that this increase in the net gain of heat from inflows during 1966-67 did not have a noticeable effect

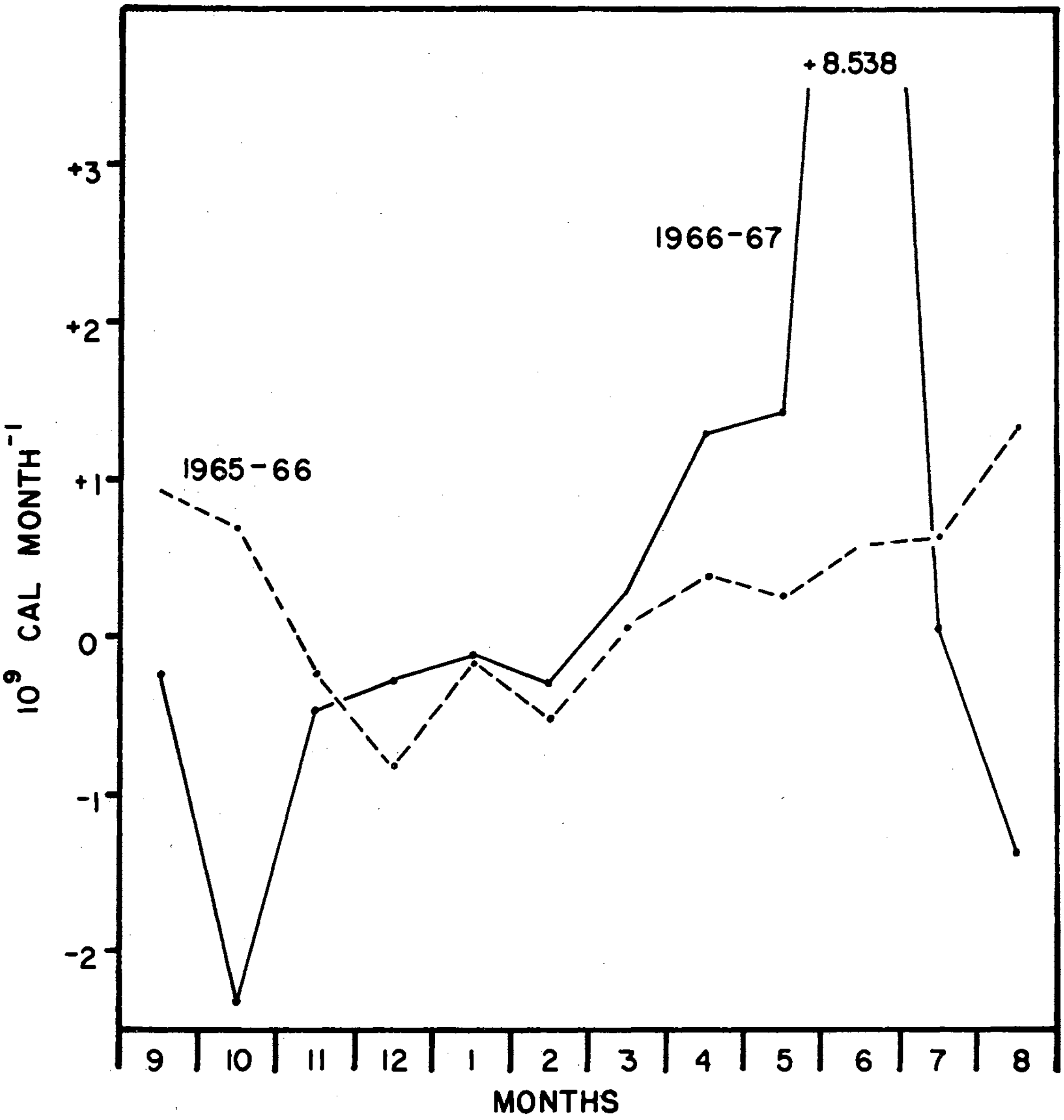

Figure 34. Comparison of monthly net gains and losses of heat due to differences in heat content of inflowing and outflowing water during 1965-66 and 1966-67

on the magnitude of the annual heat budget indicated that gains from differences in the heat content of inflows and outflows probably were not as important to the heat budget as gains from solar radiation. In fact, during the period between January and August 1967 when the reservoir had the largest net gains of heat from differences in inflows and outflows, the lowest annual heat budget was obtained (Fig. 33). The reason for the lack of effect is indicated by a comparison of heat gains and losses by inflow and outflow to the annual heat budget on a per-unit-area-of-reservoir-surface basis. Heat gained by inflows, averaged over all heating and cooling periods during 1965-67, was 306 cal cm^{-2}, and heat lost to outflows was 270 cal cm^{-2}, yielding an average net gain of only 36 cal cm^{-2} while the average annual heat budget was 17,217 cal cm^{-2}. The advective gains of heat from differences in temperature of inflows and outflows in Keystone Reservoir are surprisingly low when compared to that of other warm monomictic reservoirs. Over one-half of the annual heat budget of Lake Mead, Arizona (46,200 cal cm^{-2}), is due to advective gains from inflows (Anderson and Pritchard 1951).

The loss of heat from Keystone Reservoir due to evaporation was not determined because the "pan method" which was used to estimate evaporation in Keystone Reservoir has been severely criticized in the literature. Smith et al. (1960) indicated that pan estimates may be twice as high as the true rate of evaporation from reservoir surfaces. However, Kohler (1952) indicated that accurate pan data may be only about 10% greater than the true rate of evaporation. Evaporation from Lake Mead, which has a volume (27.9×10^9 m^3) about 34 times that of Keystone Reservoir, was estimated to be between 800 and 1200×10^6 m^3

or about 5% of the average inflows (Smith et al. 1960). Evaporation rates (Table III) for Keystone Reservoir amounted to about 4% of the average annual inflow, and therefore, do not appear to be excessively high. Evaporation heat losses accounted for about 46% of total heat losses from Lake Mead (Anderson and Pritchard 1951) and probably are the major source of heat loss from Keystone Reservoir.

CHAPTER V

NUTRIENT BALANCE OF THE CIMARRON ARM

Factors Affecting Phosphorus Distribution and Regeneration in Reservoirs

Large and often erratic fluctuations in the concentration of various phosphorus forms[1] which cannot be explained by gains from or losses to allochthonous sources have puzzled limnologists for many years (Hutchinson 1957). The complexity of the phosphorus cycle is reflected by the unpredictability of the relationship between phosphorus concentrations and primary productivity (Hutchinson 1944, Whitford and Phillips 1959). This unpredictability is the result of interactions between abiotic and biotic factors affecting the concentration of phosphorus. High energy phosphate bonds are a source of energy in the respiratory metabolism of all plants and animals; therefore, variations in the structure and function of biotic communities cause variations in phosphorus concentrations. In addition to this biotic influence, the amount of inorganic phosphorus that can remain in solution is determined by the state of ionic equilibria existing between phosphate and other inorganic ions.

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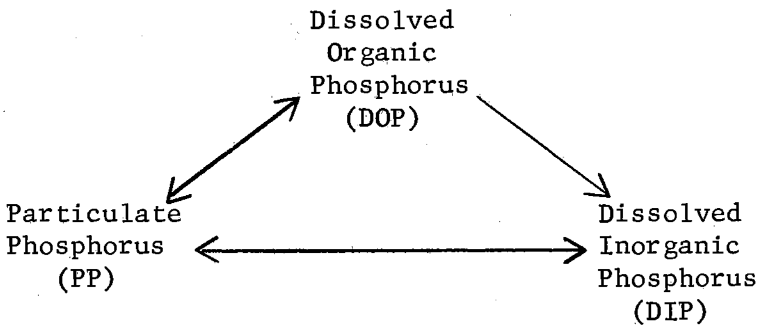
[1] Form as used in this discussion pertaining to phosphorus will be defined as the state or manner in which phosphorus exists, e.g., dissolved or particulate, inorganic or organic.

To fully understand the phosphorus cycle in reservoirs, three principle forms of phosphorus must be differentiated: dissolved inorganic, dissolved organic, and particulate phosphorus (Juday et al. 1928, Ohle 1939). Dissolved inorganic and dissolved organic phosphorus are those forms of phosphorus which are in true solution. Particulate phosphorus is primarily organic phosphorus tied up in biomass, but recently evidence has been introduced to support the hypothesis that algae also store "luxury" phosphorus as orthophosphate or as a highly labile form which readily reverts to orthophosphate when algae die (Wassink 1955, Arnon 1956, Fitzgerald 1966). Particulate inorganic phosphorus also may occur during fall overturn as ferric phosphate (Hutchinson 1957) or as calcium phosphate in some hard-water lakes (Gessner 1939). For the purpose of studying the phosphorus cycle in most reservoirs, it is sufficient to assume that most of the particulate phosphorus is organic and is associated with biomass.

There is a continual exchange of phosphorus between water and solids within natural waters, and the quantitative distribution of phosphorus between the solid and liquid phases represents a state of dynamic equilibrium (Phillips 1964). Exchange rates can vary from one biological system to another and also can vary seasonally within the same system (Watt and Hayes 1963, Rigler 1964).

The three forms of phosphorus which were distinguished in this study are generally assumed to form a transfer cycle:



The reaction, DIP → PP, represents uptake of orthophosphate by living phytoplankton and bacteria. Zooplankton do not play a significant role in this reaction (Harris 1957, Rigler 1961, Watt and Hayes 1963).

The process, PP → DOP, represents the release of organic phosphorus from dead organisms, presumably as a result of bacterial attack and leaching out by water (Hayes and Phillips 1958, Watt and Hayes 1963), and the elimination of incompletely digested food containing organic phosphorus by zooplankton, especially during periods of superfluous feeding when phytoplankton density is high (Redfield 1958, Harris 1959, Pomeroy et al. 1963, Satomi and Pomeroy 1965, and Barlow and Bishop 1965). Superfluous feeding by zooplankton may begin when phytoplankton biomass reaches about 3 g m^{-3} (wet weight)(Beklemishev 1961). Three g biomass m^{-3} is approximately equivalent to 6-12 mg chlorophyll m^{-3} (Strickland and Parsons 1960). The annual mean concentration of chlorophyll a in Keystone Reservoir during 1966-67 was more than twice the concentration at which superfluous feeding may occur (Spangler 1969). Therefore, zooplankton probably play an important role in the phosphorus cycle of Keystone Reservoir.

The return process, DOP → PP, represents the uptake of dissolved organic phosphorus compounds by bacteria, and possibly phytoplankton and certain protozoans (Watt and Hayes 1963). Krogh (1931) concluded that no multicellular animals take up dissolved organic substances to any significant extent. However, Chu (1946) and Abbott (1957) found that phytoplankton can derive phosphorus by the uptake of soluble organic compounds. Apparently zooplankton do not play a part in this transfer.

DOP ⟶ DIP is the result of several simultaneous processes:

(1) the release of DIP from organic compounds which have been broken down by bacteria; the source could be dissolved compounds taken up from water or obtained from dead cells, organic detritus, or organic colloids;

(2) the return of DIP to the water by phytoplankton and bacteria as a result of the exchange by which inorganic phosphate is continually passed into and out of living cells (Hayes and Phillips 1958, Watt and Hayes 1963); and

(3) autodephosphorylation by phosphatase activity of labile organic phosphorus compounds contained within dead organisms (Matsue 1940, Grill and Richards 1964, Fitzgerald 1966).

In addition to biotic effects, the distribution and flux of phosphorus in reservoirs is influenced by the chemical equilibria of other ionic species. Accumulation of phosphorus in the hypolimnion and in the sediments occurs by precipitation of insoluble phosphorus-bearing compounds and sedimentation of phosphorus-bearing particulate matter. Precipitation of phosphorus is accomplished primarily by oxidized heavy metals, mainly ferric iron (Hutchinson 1957). If reducing conditions are present in the hypolimnion or sediments, insoluble Fe^{+++} is reduced to soluble Fe^{++}, and PO_4 is slowly released into the hypolimnion. In alkaline waters where there is an excess of calcium, phosphorus also may precipitate as tricalcium phosphate, $Ca_3 (PO_4)_2$ (Neess 1949). This salt is converted to the more soluble di- and mono-calcium phosphates as the pH of the water is reduced. Equilibrium with hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, may control phosphate concentrations in the Great Lakes (Kramer 1964). Falls (1969) has suggested that this heterogeneous reaction could control or at least buffer the phosphorus content of the waters of Keystone Reservoir.

Distribution of Phosphorus in Keystone Reservoir

Concentrations of total phosphorus in the Cimarron arm ranged from a minimum of 10 mg P m^{-3} at Station III in January 1967 to a maximum of 994 mg P m^{-3} at Station I in August 1967 (Table XXIX). High concentrations of dissolved forms of phosphorus usually were associated with low concentrations of particulate phosphorus, and high concentrations of particulate phosphorus usually were associated with low concentrations of dissolved phosphorus. DIP was absent or below the minimum detectable concentration in surface waters of Stations III and IV in September 1966, Station III in January 1967, Stations II and III in March 1967, and Stations III and IV in June 1967. These were the only occasions when inorganic phosphorus may have been limiting to primary productivity, and inorganic phosphorus may not have been limiting on these dates since it is well known that algae store "luxury" phosphorus in excess of their needs (Wassink 1955, Arnon 1956, Fitzgerald 1966). DOP was undetectable or in extremely low concentrations throughout the water column at Stations II, III, and IV in September and November 1966. PP was present in all samples collected during 1966-67.

TABLE XXIX

MINIMUM AND MAXIMUM CONCENTRATIONS (mg P m^{-3}) OF PHOSPHORUS MEASURED AT ANY DEPTH AT EACH STATION DURING 1966-67

Form of Phosphorus	Station I		Station II		Station III		Station IV	
	min	max	min	max	min	max	min	max
Total P	87	994	13	456	10	174	22	309
DIP	34	850	0	116	0	102	0	176
DOP	2	134	0	46	0	23	0	30
PP	22	790	8	388	4	121	0	144

In general, concentrations of total phosphorus increased with depth and decreased downstream (Table XXX). Increases in concentrations of phosphorus between Stations III and IV were caused almost entirely by increases in concentrations of DIP. The annual mean concentration of DIP at Station IV was 48.8% higher than the annual mean concentration of DIP in the rest of the Cimarron arm, excluding Cimarron River data. This increase in DIP at Station IV supports the hypothesis that water in the lower end of the Cimarron arm during 1966-67 was primarily of Arkansas River origin. Phosphate concentrations in the Arkansas arm averaged 48% higher than phosphate

TABLE XXX

ANNUAL MEANS OF CONCENTRATIONS (mg P m^{-3}) AND AMOUNTS (mg P m^{-2}) OF PHOSPHORUS IN KEYSTONE RESERVOIR DURING 1966-67

Depth (m)	Stations													
	I		II		III		IV	I		II		III		IV
1	545	*	100	*	83	*	114	249	*	64	*	48	*	50
5			92		78		113			71	*	40		47
			*							*				
10			171	*	86	*	118			129	*	47		47
					*									
14	Total P				106		123	Particulate P				55		47
							*							
18							132							60
mg m^{-2}	858	*	1029	*	1248	*	2174	487	*	771		681	*	910
1	259	*	24		29	*	54	37	*	12		7		10
5			14		31	*	60			7		7	*	13
										*				
10			29		34	*	62			13	*	4	*	9
												*		
14	Dissolved Inorganic P				42		57	Dissolved Organic P				10		8
18							64							8
mg m^{-2}	330	*	179	*	475	*	1084	41	*	79	*	93	*	177

* indicates significant difference ($\alpha = 0.10$) between means using depth x date MS as error term to test for differences among depths within stations and station x date MS to test for differences among stations within depths.

concentrations in the Cimarron arm in 91 observations made by the U. S. Geological Survey during 1965-66. The annual mean concentration of DIP in the Arkansas River was 24% higher than the annual mean concentration in the Cimarron River during 1966-67 (Table XV).

Concentrations of phosphorus were greatest in the density current flowing along the bottom of the Cimarron arm (Table XXX). Considerable reductions occurred in the concentration of PP in the density current between Stations I and II and between Stations II and III. These reductions appeared to be due to sedimentation of PP since significant increases in DIP did not occur. Reductions in PP between Stations I and II of 48% and between Stations II and III of 57% (Table XXX) closely paralleled reductions in suspended solids between Stations I and II of 46% and between Stations II and III of 58% (Table XXV). This relationship suggests that the high concentrations of phosphorus at Station I were due to phosphorus associated with silt and clays suspended in Cimarron River inflows. Annual mean concentrations of DIP exceeded annual mean concentrations of PP at Stations I and IV, while concentrations of PP exceeded concentrations of DIP at Stations II and III (Table XXX). Concentrations of DOP were highest at Station I and were uniformly low throughout the rest of the Cimarron arm.

Phosphorus Budget of the Cimarron Arm

The phosphorus content of the Cimarron arm was calculated by multiplying the average concentration of phosphorus at each meter of depth by the volume of water contained in that layer and summing the products (Fig. 35). In general, total phosphorus content increased throughout the year, with most significant increases occurring during

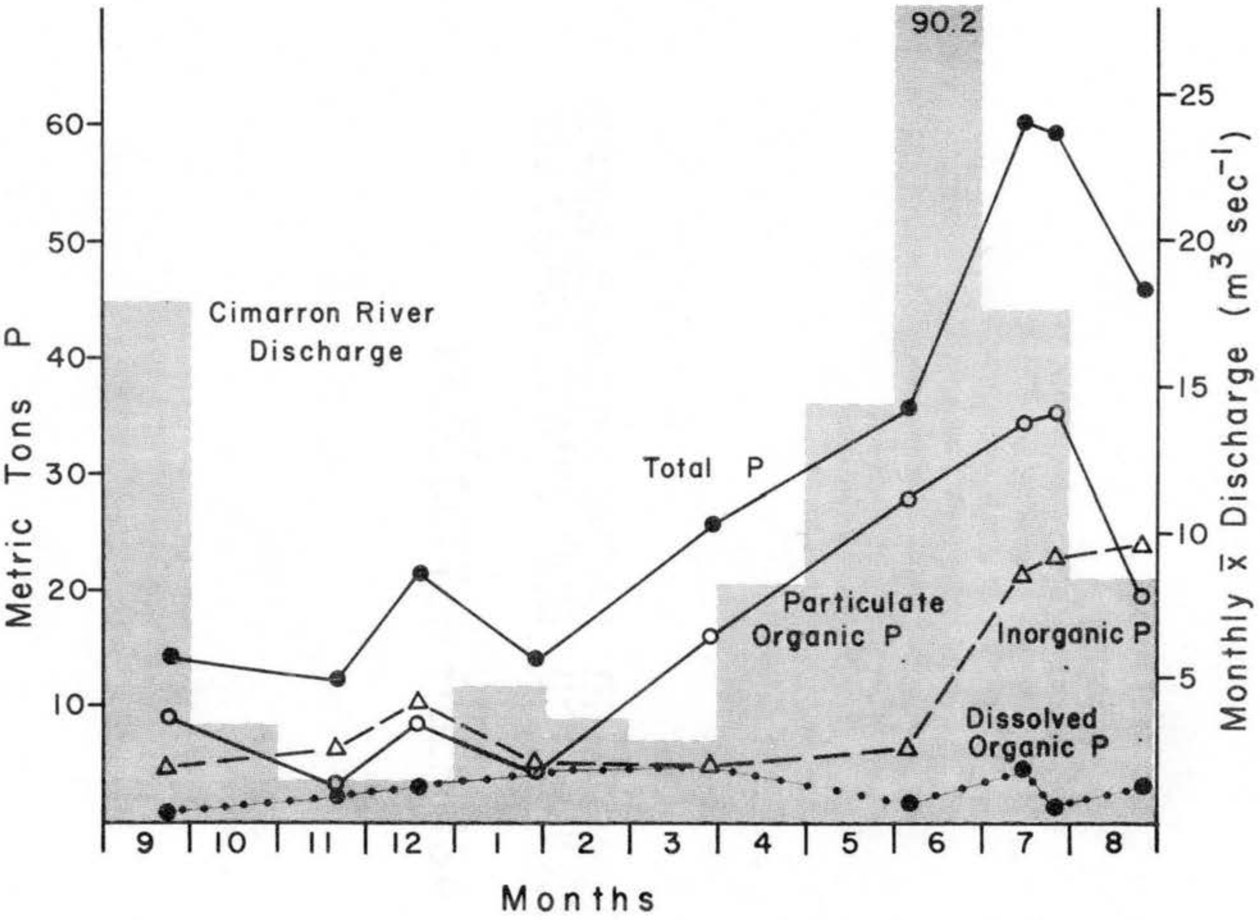


Figure 35. Relation of phosphorus content of Cimarron arm to Cimarron River discharge during 1966-67

high inflows of the Cimarron River in June and July 1967. Temporal variations in total phosphorus content closely followed variations in content of PP, which was the most abundant form of phosphorus during most of the year. DOP content of the Cimarron arm remained fairly constant during 1966-67. DIP content remained relatively constant until June 1967. Between September 1966 and June 1967, inflows of DIP apparently were being offset by losses through outflows, conversion to PP, and precipitation. Gains in DIP exceeded losses during high inflows in June 1967 and resulted in a significant increase in DIP content of the Cimarron arm. Large gains of phosphorus during June and July apparently saturated the reservoir system with inorganic phosphate as indicated by a relatively small increase in DIP content between July and August 1967 and a large decrease in PP content (Fig. 35). Of the total loss in PP content between July and August 1967, only 5.9% was converted to DIP and only 11.8% was converted to DOP (Table XXXI). Apparently 82.3% of the decrease in PP content was due to precipitation to sediments. Between 23 July 1967 and 24 August 1967, DIP increased from 38.6% to 51.3% of total P, while PP decreased from 59.3% to 42.1% of total P (Table XXXI).

The gain in total phosphorus content of the Cimarron arm from 14.3 to 45.8 metric tons between September 1966 and August 1967 represents an increase of 320%. This rate of increase is larger than any other known from the literature and is 12.8 times the rate of increase of phosphorus in Lake Erie during the past 20 years (Verduin 1964, 1967). Concentrations of phosphorus recorded for Missouri River Reservoirs are higher than average concentrations found in Keystone Reservoir, but the phosphorus content of Keystone Reservoir is increasing at a greater rate (Table XXXII). Differences in concentration may be due to differences in the age of the reservoirs or may be due to the use of different analytical methods. Methods used to measure phosphorus in the 1950's are not considered to be as reliable as methods used for phosphorus analyses in the present study. The importance of using modern methods was pointed out by Rigler (1964).

TABLE XXXI

RELATION OF CONCENTRATIONS (mg P m^{-3})* OF THE THREE FORMS OF PHOSPHORUS TO THE DECREASE IN TOTAL PHOSPHORUS CONTENT DURING JULY AND AUGUST 1967

	Total P	DIP		DOP		PP	
Date	$\bar{X}$	$\bar{X}$	% of total	$\bar{X}$	% of total	$\bar{X}$	% of total
7/23/67	194	75	38.6	4	2.1	115	59.3
8/24/67	152	78	51.3	10	6.6	64	42.1

*All concentrations are volume-weighted means.

A phosphorus budget of the Cimarron arm of Keystone Reservoir was calculated to gain insight into the mechanisms causing the large increase in total phosphorus content during 1966-67 (Table XXXIII). Total inflow and outflow of phosphorus in the Cimarron arm were estimated by the method described by Hrbacek (1966). Inflow of phosphorus was calculated by multiplying Cimarron River discharge by the concentration of phosphorus in the Cimarron River at its entrance to the reservoir. Outflow of phosphorus was calculated by multiplying Cimarron River discharge by the concentration of phosphorus in the density current in the hypolimnion at the lower end of the Cimarron arm. In calculating outflow of phosphorus by this method, the assumption was made that all water entering the reservoir from the Cimarron River was discharged from the hypolimnion through sluice gates. This assumption was justifiable since the Cimarron River discharge was only 17% as great as the total reservoir outflow (Table III), and studies of stratification and currents in the Cimarron arm indicated that the hypolimnetic density current flowed through the Cimarron arm to the dam. Gains from and losses to waters of Arkansas River origin which flowed into and out of the Cimarron arm were considered equivalent and ignored in this analysis.

TABLE XXXII

RATE OF INCREASE IN TOTAL PHOSPHORUS IN RESERVOIRS OF THE GREAT PLAINS

Reservoir	Time Period	Increase in Concentration (mg P m^{-3})	Rate of Increase
Keystone	9/66-8/67	49 to 157	320% yr^{-1}
Garrison*	1955-57	180 to 790	219% yr^{-1}
Gavins Point*	1956-57	190 to 290	153% yr^{-1}
Fort Randall*	1952-57	40 to 260	93% yr^{-1}

*Neel (1967).

TABLE XXXIII

PHOSPHORUS BUDGET OF THE CIMARRON ARM DURING 1966-67

(Metric Tons of P)

	Total P	DIP	DOP	PP
Total inflow	108.3	48.9	6.0	52.8
% of total P		45%	6%	49%
Total outflow	66.8	26.1	4.9	35.8
% of total P		39%	7%	54%
Amount retained	41.5	22.8	1.7	17.0
% of total P		55%	4%	41%
% of inflow retained	38.3%	46.6%	25.7%	32.1%
Total content of water (9/66)	14.3	4.6	0.6	9.1
% of total P		32%	4%	64%
Total content of water (8/67)	45.8	23.6	3.0	19.2
% of total P		52%	6%	42%
Increase in content of water	31.4	19.0	2.3	10.1
% of total P		60%	8%	32%
Contribution by rainfall*	1.0	1.0		
Calculation of apparent loss to sediments				
Inflow retention	41.5	22.8	1.7	17.0
+Rainfall contribution	+1.0	+1.0		
±Conversion of forms		+0.8(+5%)	+0.7(+4%)	-1.5(-9%)
-Increase in water	-31.4	-19.0	-2.3	-10.1
=Apparent loss	11.1	5.6	0.1	5.4
% of net influx lost to sediments	26%	24%	6%	32%
% of total P lost to sediments		50%	1%	49%

---

*The contribution of DIP by direct rainfall is the average of five estimates based on rates reported in the literature (Chalupa 1960, Miller 1961, Tamm 1951, Tamm 1953, Voight 1960).

Of the 108.3 metric tons of total phosphorus contributed by the Cimarron River, 38.3% was retained in the reservoir. Approximately 74% of the amount retained appeared as an increase in phosphorus content of the water, and the remaining 26% apparently was lost to sediments by chemical precipitation and sedimentation of particulate matter. The retention of 38.3% of the total influx of phosphorus to the Cimarron arm is similar to retentions reported for other reservoirs (Table XXXIV).

TABLE XXXIV

RETENTION OF PHOSPHORUS BY RESERVOIRS

Reservoir	Reference	Time Period	% of Total Inflow Retained
Keystone	Present study	1966-67	38.3
Slapy, Czech.	Hrbacek (1966)	1959-60	59.0
Garrison	Neel et al. (1963)	1955-56	62-65
Lake Mendota	Rohlich (1963)	1955-56	28.9
Cimljanskoe, Russia	Fesenko and Rogozkin (1961), from Hrbacek (1966)		35.0
Tystrup So Lake	Berg (1943)		44.3

To determine the net change in forms of phosphorus in the reservoir, the relative importance of DIP, DOP, and PP to the total amount of phosphorus retained in the reservoir was compared to the relative importance of DIP, DOP, and PP to the total amount of phosphorus appearing as an increase in phosphorus content of the water. Using this approach it was estimated that of the 17.0 metric tons of PP retained in the reservoir, 1.5 metric tons of PP were converted to other forms of phosphorus by biological activity. Approximately 9.8 metric tons were converted to DIP and 0.7 metric tons were converted to DOP (Table XXXIII).

The total influx of phosphorus into Keystone Reservoir is obviously much greater than the 108.3 metric tons contributed by the Cimarron River, since the Cimarron contributes only 17% of the total inflow. Assuming equal concentrations of phosphorus in all inflow, Keystone Reservoir would have a total inflow of 637 metric tons of P year^{-1}. Assuming that about 38% of this amount was retained, the reservoir's total phosphorus content would increase by 242 metric tons of P year^{-1}. This is probably an underestimate since the concentration of DIP in the Arkansas River is higher than the concentration in the Cimarron River, and the percentage (46.6%) of DIP retained was higher than the percent retention for PP (32.1%) or DOP (25.7%).

From the mass balance calculations presented in Table XXXIII, it is apparent that the increase in total phosphorus content of the Cimarron arm was primarily due to retention of phosphorus contributed by inflows from the Cimarron River. These calculations based on only a 12-month observation period may either underestimate or overestimate the actual long-term rate of eutrophication[1] of Keystone Reservoir.

The conclusion that increases in total phosphorus content of the Cimarron arm were due to contributions of inflows was questioned by Falls (1969), largely because of misinterpretation of personal communications. Falls (1969) stated,

> Eley (personal communication) found that the total phosphate concentration in the reservoir increased approximately 320% from September 1966 to August 1967. The possibility of inorganic chemical reactions controlling the concentrations of dissolved inorganic phosphate in natural waters is frequently ignored.

Total phosphorus, not phosphate, increased 320%. Falls (1969) suggested that the increase in phosphorus content of the Cimarron arm was due to an increase in the amount of phosphate required to saturate hydroxyapatite. By comparing selected DIP concentrations observed during the present study to concentrations calculated from equilibrium relationships, Falls (1969) concluded that the waters of Keystone Reservoir were supersaturated with respect to apatite by a factor of about 10, and that this unlikely situation was a result of slowness of the precipitation reaction or of systematic errors in equilibrium calculations or phosphorus analyses. The possibility of inorganic equilibria affecting the DIP content of the Cimarron arm was not ignored in calculating the phosphorus budget. In fact, calculations indicated that 24% of the total amount of DIP retained from inflows was lost to the sediments by precipitation. This precipitation of DIP may have resulted from supersaturation of apatite, but it is likely that precipitation of $FePO_4$ was also important. It is apparent from Figure 35 that increases

---

[1] Eutrophication in this study is defined as an increase in the nutrient content of a reservoir by allochthonous sources, either of natural or domestic origin.

in the total phosphorus content of the Cimarron arm between September 1966 and June 1967 were primarily due to increases in PP. An increase in the amount of phosphate required to saturate apatite would not result in an increase in PP.

Ammonia and Nitrate Nitrogen

The accuracy and precision involved in estimating concentrations of ammonia-nitrogen (NH_3-N) and nitrate-nitrogen (NO_3-N) were not considered to be sufficient to warrant detailed analysis of nitrogen data. Annual means of concentrations and amounts of NH_3-N (Table XXXV) and average concentrations of NO_3-N (Table XXXVI) indicate the order of magnitude of concentrations during 1966-67. Significantly higher concentrations were found at Station I, but no other differences in concentrations among stations or among depths within stations were demonstrated.

Concentrations of NH_3-N exceeded 12 g N m^{-3} in the anoxic hypolimnion of Keystone Reservoir during July 1966 (Eley et al. 1967). No build-up in concentrations of NH_3-N occurred in the hypolimnion of Keystone Reservoir between September 1966 and August 1967. Maximum concentrations of NH_3-N were less than 5 g N m^{-3}, and these were recorded in the aerated surface waters of Station I during December 1966 and January 1967. Significant concentrations of NH_3-N would not be expected in water saturated with oxygen. Concentrations of NH_3-N apparently were below the minimum detectable concentration of the direct nesslerization method, and values observed in the reservoir probably were the result of inferences by aliphatic and aromatic amines and chloramines or other unidentified nitrogen-bearing compounds.

High concentrations obtained at Station I support this hypothesis.

TABLE XXXV

ANNUAL MEANS OF CONCENTRATIONS (mg N m^{-3}) AND AMOUNTS (mg N m^{-2}) OF AMMONIA-NITROGEN IN KEYSTONE RESERVOIR DURING 1966-67

Depth (m)	Stations						
	I		II		III		IV
1	1334	*	255	*	170	*	328
5			232		184		406
10			201		317		332
14					385		282
18							344
m^{-2}	1818		1911	*	3564	*	5915

*indicates significant difference ($\alpha = 0.10$) between means using depth x date or station x date MS as error terms.

Faulty reagents invalidated results of all NO_3-N analyses between September 1966 and June 1967. Concentrations observed during June, July, and August 1967 ranged from 50 to 460 mg N m^{-3} and were lower than the annual mean concentrations of the Cimarron and Arkansas Rivers during 1965-67 (Table XV).

TABLE XXXVI

AVERAGE CONCENTRATIONS (mg N m^{-3}) OF NITRATE-NITROGEN IN KEYSTONE RESERVOIR DURING JUNE, JULY, AND AUGUST 1967

Depth (m)	Stations			
	I	II	III	IV
1	330 *	50	130	180
5		130	150	230
10		200	120	170
14			120	180
18				120

*indicates significant difference ($\alpha = 0.05$) between means ($lsd_{.05} = 176$).

CHAPTER VI

COMMUNITY METABOLISM OF KEYSTONE RESERVOIR

Definition of Terms and Abbreviations

Terminology involved in the concept of community metabolism has been established for several years and has been reviewed by Odum and Hoskins (1958), Davis (1963), and Byers (1963a). However, variations in the definition of terms exist in the literature. Common terms will be abbreviated in this discussion and are defined below.

Gross Productivity (Pg) - The rate of energy stored as reduced organic material or the liberation of oxygen as a by-product of photosynthesis by photoautotrophic organisms.

Community Respiration (Rt) - The rate of oxidation of organic matter to provide energy for the life processes of the biota and the chemical oxygen demand of the abiotic components of the community.

Net Productivity (Pn) - The net rate of energy storage by the community during a 24-hr period or the difference between Pg and Rt.

Gross Productivity to Community Respiration Ratio (Pg/Rt) - The ratio of gross productivity to community respiration must be unity (Pg/Rt = 1.0) in a balanced steady state system, if no export or import occurs (Beyers 1963a). If some event should disturb this ratio in such a manner that it becomes greater or less than unity, an increase or reduction of the biomass through growth or starvation will take place, and the ratio will tend to return to unity.

Efficiency of Production - The ratio, expressed as percent, of gross productivity to the quantity of light energy of suitable wave length which falls on the system.

Euphotic Zone (EZ) - The depth of penetration of 1% of the intensity of light entering the water surface.

Method of Measurement

Procedures

A modification of the diurnal[1] oxygen curve method of Odum and Hoskin (1958) was used to estimate the rate of community metabolism of the Cimarron arm of Keystone Reservoir during 1966-67. The concentration ($g\ O_2\ m^{-3}$) of dissolved oxygen was determined at each meter of depth from surface to bottom at 3-hr intervals during a 24-hr period. Concentrations of oxygen in the water column were summed to obtain $g\ O_2\ m^{-2}$, and the need for considering vertical transport of oxygen was eliminated (Odum et al. 1963). The average rate-of-change ($g\ O_2\ m^{-2}\ hr^{-1}$) was calculated for each 3-hr interval. A correction for atmospheric reaeration was calculated by multiplying a diffusion constant (k) by the average oxygen saturation deficit of the surface waters during each 3-hr interval. The diffusion constant (k) was estimated by averaging k values determined for each nighttime sampling interval by the formula,

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[1] Diurnal is commonly used to designate events pertaining to day only, while the diurnal oxygen curve method involves measurements of oxygen concentration during a 24-hr period. In this discussion, the method will be referred to as the O_2 curve method.

$$k = \frac{q_n - q_{n+1}}{S_n - S_{n+1}}$$

where, $k = g\ O_2\ m^{-2}\ hr^{-1}$ at o% oxygen saturation

q_n = rate-of-change of the surface $g\ O_2\ m^{-3}$ at nighttime n,

q_{n+1} = the rate-of-change of the surface $g\ O_2\ m^{-3}$ at nighttime n+1,

S_n = the oxygen saturation deficit of the surface water at nighttime n, and

S_{n+1} = the oxygen saturation deficit of the surface water at nighttime n+1,

or by direct measurement using a plastic dome and Scholander device (Copeland and Duffer 1964). The corrected average oxygen rate-of-change for each 3-hr interval was plotted against time, and a daytime respiration line was extrapolated between pre-sunrise and post-sunset negative rate-of-change points (Fig. 36) (Odum and Wilson 1962). The area above the nighttime negative rate-of-change line and the daytime respiration line and below the zero rate-of-change line was considered to be an estimate of Rt. The area above the daytime respiration line and below the daytime rate-of-change line was considered to be an estimate of Pg.

A computer program was developed to compute Pg, Rt, Pn, Pg/Rt, atmospheric diffusion-in, and atmospheric diffusion-out. A listing of the program with comment cards explaining methods of calculation with examples of input and output data is presented in the Appendix. The program performed a valid O_2 curve analysis of about 90% of the data tested. Data used to test the program included 176 O_2 curves from Keystone Reservoir, 48 O_2 curves from laboratory microcosms, 16 O_2 curves from lake studies reported in the literature, and 8 O_2 curves

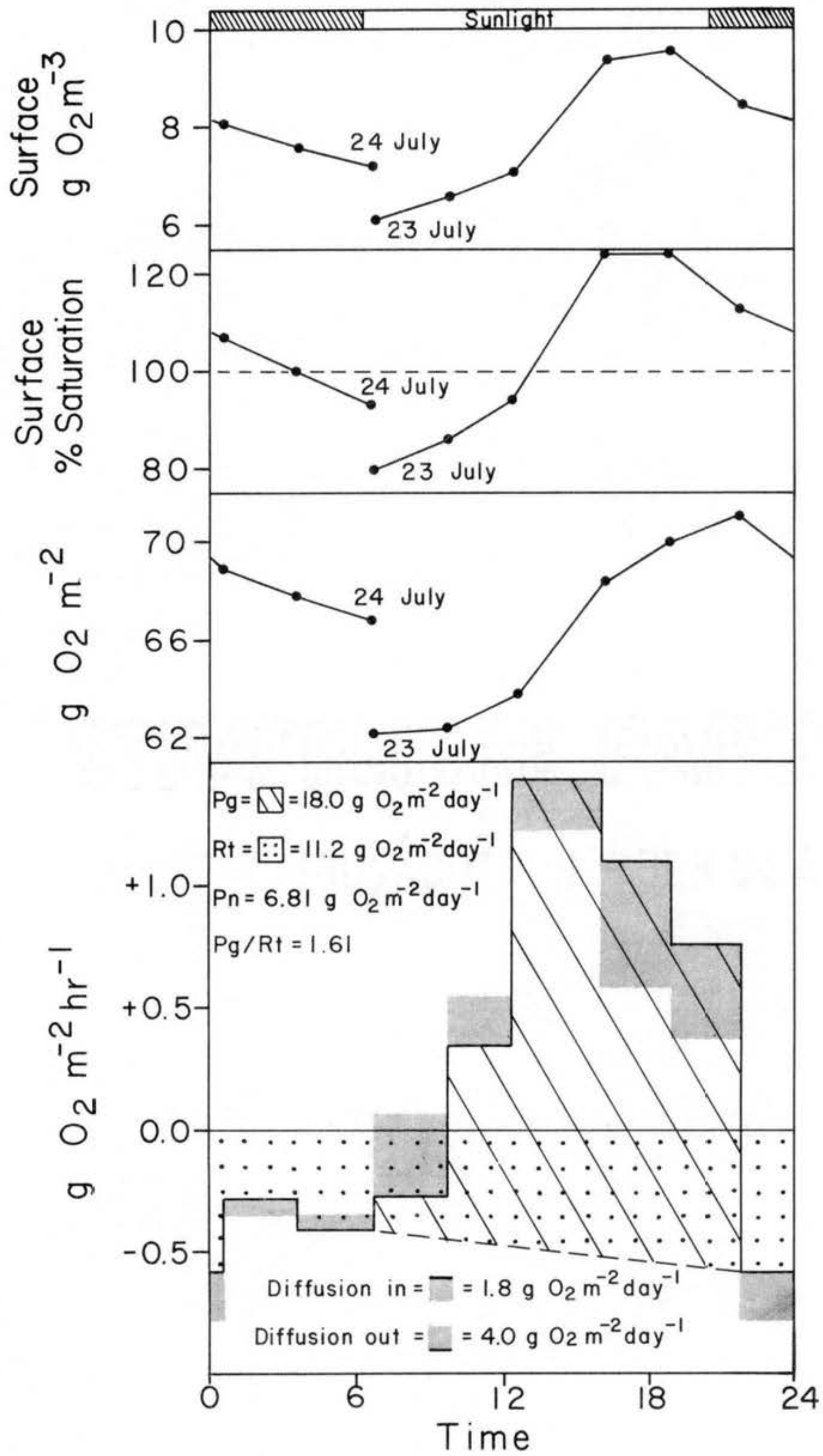

Figure 36. Community metabolism and atmospheric reaeration at Station IV, Keystone Reservoir, 23-24 July 1967, as calculated by the O_2 curve method (k = 1.98)

from Oklahoma farm ponds. When the program did not select correct points for the daytime respiration line, analyses were performed graphically by hand (Fig. 36).

Precision of the O_2 Curve Method

Mean coefficients of variation among substations within stations for Pg ranged from 2.72% for Station I to 9.36% for Station IV (Table XXXVII). Mean coefficients of variation among substations within stations for Rt ranged from 1.71% for Station I to 11.67% for Station IV. Average coefficients of variation among replicate observations in eight laboratory microcosms containing water from Keystone Reservoir were 1.8% for Pg and 5.7% for Rt.

TABLE XXXVII

AVERAGE COEFFICIENTS OF VARIATION OF THE OXYGEN CURVE METHOD IN KEYSTONE RESERVOIR

	Stations			
Parameter	I CV(%)	II (CV%)	III CV(%)	IV CV(%)
Pg	2.72	4.27	3.32	9.36
Rt	1.71	4.28	5.54	11.67

Estimation of Daytime Respiration

Estimates of Pg and Rt by the O_2 curve method as used by Odum and Hoskins (1958), the light and dark bottle O_2 method (Gaarder and Gran 1927), and the pH-CO_2 curve method (Byers and Odum 1959) are based on the assumption that the rate of respiration is constant during both day and night. If day respiration exceeds night respiration, both Pg and Rt are underestimated.

A convincing amount of evidence has accumulated to indicate that the average rate of respiration in the light is higher than the average rate of respiration in the dark (Jackson and McFadden 1954; Ryther 1954; Verduin 1957, 1960; Gessner and Pannier 1958; Weis and Brown 1959; Odum and Wilson 1962; Odum, Beyers, and Armstrong 1963; Odum et al. 1963; Lorenzen 1963; Hoch, Owens, and Kok 1963; Beyers 1963a, 1963b, 1965). This conclusion is based primarily on observations that the maximum rate of respiration often occurs immediately after sunset and that the rate declines through the night to a minimum before sunrise. It is assumed that the rate of respiration increases during the day from a pre-sunrise minimum to a post-sunset maximum. The mathematical function describing this increase is not known. Therefore, the rate of respiration may increase linearly or exponentially. Odum, Beyers, and Armstrong (1963) stated that respiration diminishes logarithmically during the night as the storage of labile organic matter decreases. They constructed an electrical analogue circuit which simulated this characteristic metabolic pattern of balanced aquatic systems. Beyers (1963a, 1965) found this pattern of respiration occurring about 82% of the time in laboratory microcosms. In addition to diurnal variations in the rate of respiration, variations in the rate of photosynthesis and in photosynthetic capacity have been found (Schimada 1958, Hastings et al. 1961, Lorenzen 1963, Palmer et al. 1964, Newhouse et al. 1967).

Mechanisms which have been proposed to explain the diurnal variation in metabolic rates are:

1. an internal "biological clock" which is dependent on light but independent of temperature (Hastings et al. 1961, Palmer et al. 1964);
2. differences in the rate of O_2 diffusion caused by differences in O_2 tension, which is also affected by the rate of water mixing (Franck and French 1941, Gessner and Pannier 1958); and
3. the amount of stored labile organic matter, acting through competition between substrate electrons and photosynthetic reductant for components of the respiratory electron transport system (Weis and Brown 1959).

Experiments were conducted on 4-7 July 1968 to determine if the observed increase in daytime respiration was approximated by a line drawn between pre-sunrise and post-sunset negative rate-of-change points (Fig. 37). The increase in daytime respiration was estimated by average negative rates of O_2 change immediately after light was extinguished in four replicate-pairs of laboratory microcosms containing water from Keystone Reservoir and receiving photo-periods of different duration. Microcosms were randomly chosen for treatments on each day. On 4 July and 6 July, all microcosms received a 12-hr photoperiod. Lack of differences among rates-of-change of treatment pairs when treated alike indicated the similarity of experimental units.

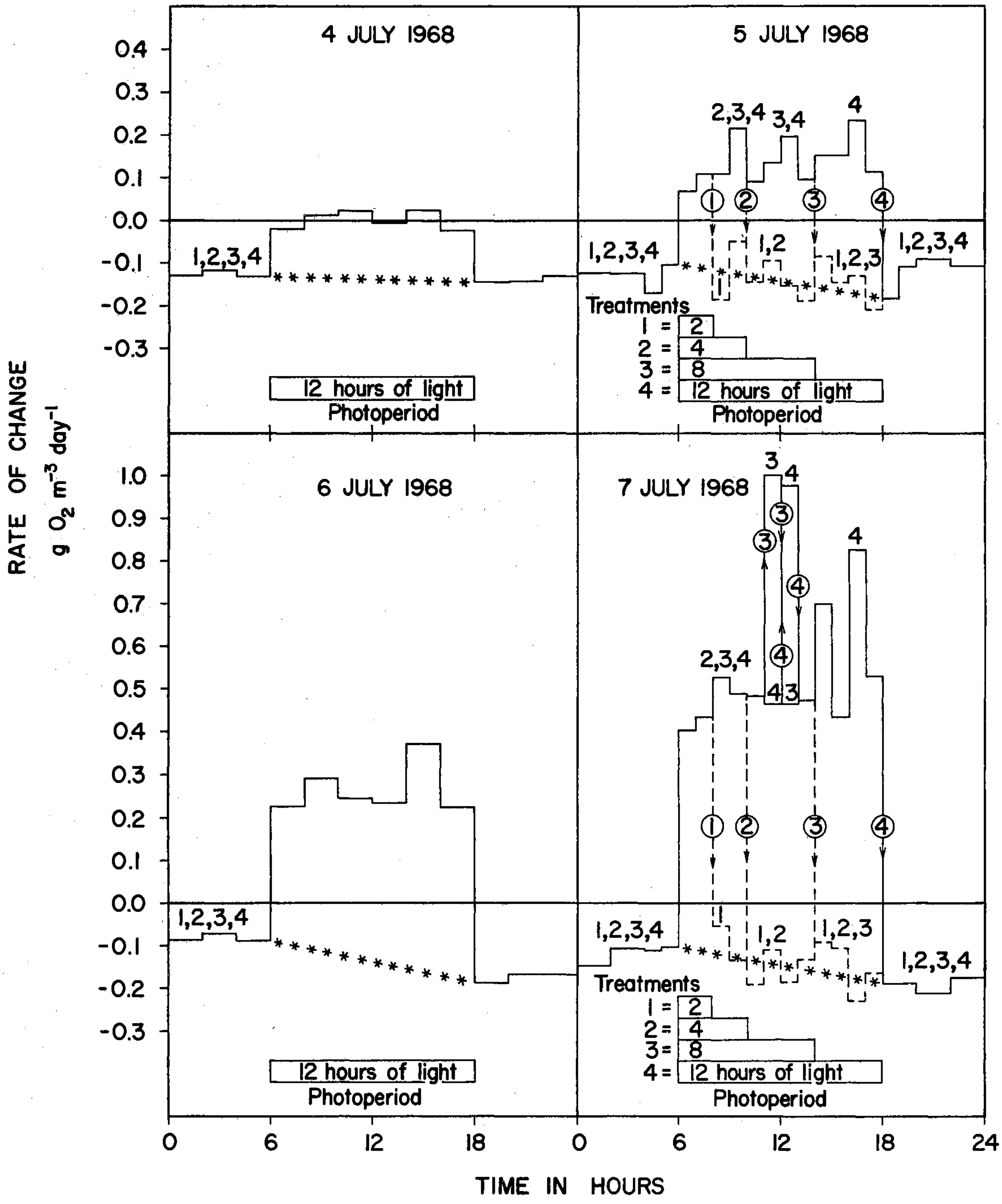

Figure 37. Effect of a varied photoperiod on the rate-of-change of oxygen in eight laboratory microcosms during the early stages of succession. --- = negative rate-of-change observed after light was extinguished in treatments receiving a photoperiod shorter than 12 hours. *** = hypothetical daytime respiration line of treatments receiving a 12-hr photoperiod. When treatment $\bar{X}$ rates-of-change were not significantly different ($\alpha = 0.05$), $\bar{\bar{x}}$ is represented by a single line. Numbers on the rate-of-change line indicate which treatments are represented by that segment of the line.

A statistical analysis of data shown in Fig. 37 indicated that slopes of least squares regression lines fitted through observed negative rates-of-change were significantly less ($\alpha = 0.05$) than zero, suggesting an increase in the rate of daytime respiration (Fig. 38). Slopes of regression lines were not significantly different ($\alpha = 0.05$) from slopes of hypothetical daytime respiration lines.

Comparison of the O_2 Curve Method With Other Methods

Few comparisons have been made between bottle and free-water methods, although it is generally conceded that bottle methods underestimate actual metabolic rates (Ryther 1956a, Talling 1957, Rodhe 1958, Verduin et al. 1959, Verduin 1960). Talling (1957) found metabolic rates estimated from O_2 changes to be greater than L & D bottle rates by 1.9 for Gebel Aulia Reservoir and 1.6 for a bay of Lake Victoria. L & D bottle rates were found to be less than one-half rates measured under natural conditions in western Lake Erie (Verduin et al. 1959).

Not all investigators agree that higher rates obtained by free-water methods are correct. Vinberg (1960) defended the L & D bottle method and concluded that differences between free-water and bottle methods were due to incorrect adjustments for atmospheric reaeration and lack of consideration of gas exchange with bottom muds. L & D bottle estimates of photosynthesis were slightly higher than estimates based on natural pH changes in Sanctuary Lake (Jackson and McFadden 1954). Productivity estimates by L & D bottles in Amaravathy Reservoir, India, were higher than estimates made from natural O_2 changes, but the techniques of measurement and calculation were not described

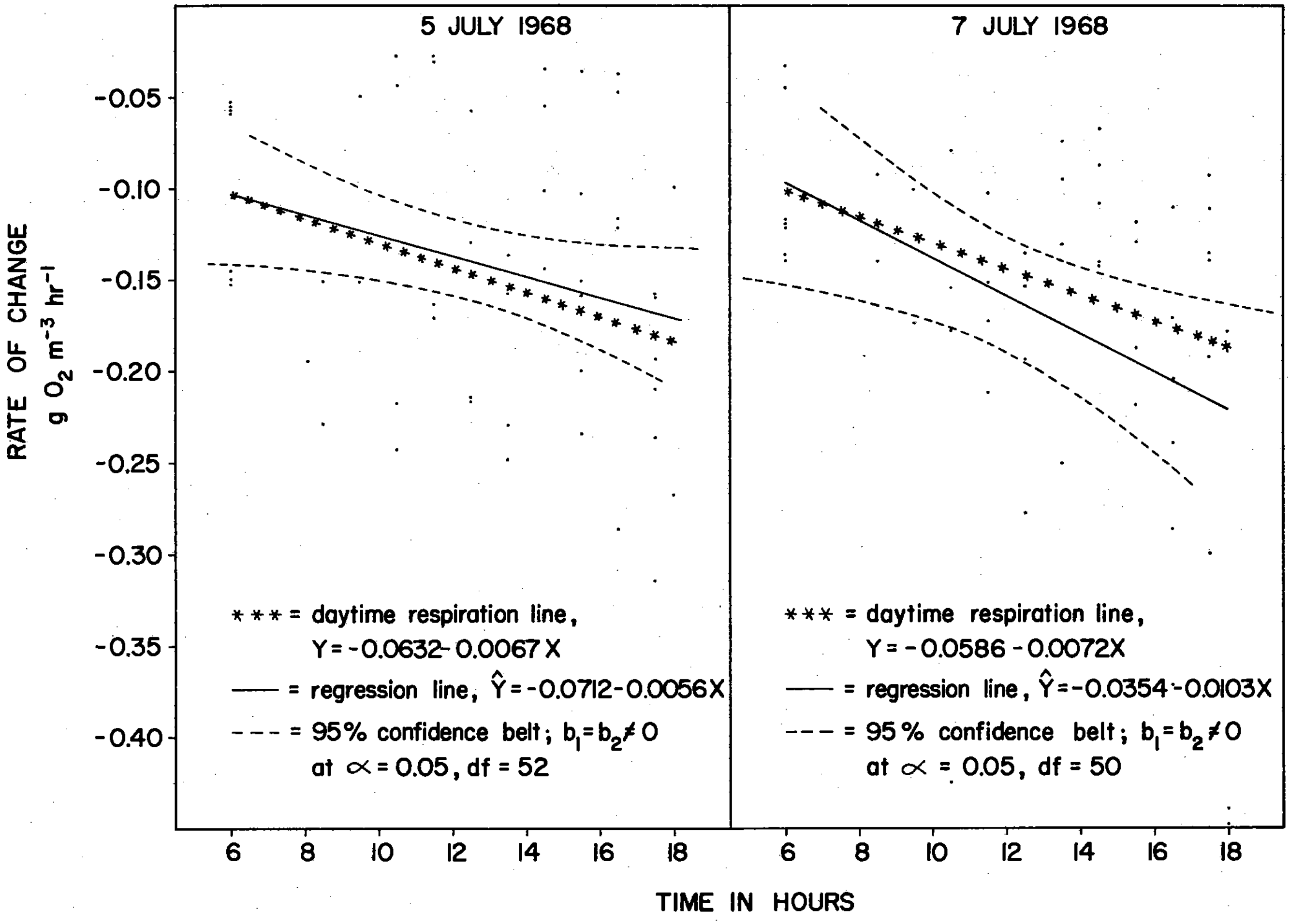

Figure 38. Comparison of hypothetical daytime respiration lines drawn between $\bar{X}$ negative rate-of-change points at the beginning and at the end of the light period with least squares regression lines fitted through observed rates of community respiration

adequately (Sreenivasan 1965).

Apparently no comparisons between free-water O_2 and CO_2 curve methods were reported in the literature before 1957 (Talling 1957). Metabolic rates estimated from changes in pH-CO_2 were found to exceed rates obtained by O_2 changes by Park et al. (1958) for Texas bays and by Megard (1961) for two lakes of the Chuska Mountains, New Mexico. Verduin (1960) concluded that phytoplankton communities of western Lake Erie during exponential growth use considerable CO_2 for carboxylation in the synthesis of organic acids above that used in glucose production; therefore, CO_2 estimates would be expected to exceed O_2 estimates. Odum et al. (1963) found that rates determined by CO_2 changes exceeded rates determined by O_2 changes in polluted Texas bays having nighttime anaerobic conditions. Beyers (1963a) concluded that the two methods agreed fairly well in observations in laboratory microcosms, with O_2 rates averaging about 1.2 times CO_2 rates. Beyers felt the discrepancy between his results and the results of other investigators might have been caused by lower light intensities (1000 ft-c) in the laboratory than under natural conditions of sunlight.

A direct comparison of the O_2 curve method, pH-CO_2 curve method, and L & D bottle method was made in July 1968. Eight laboratory microcosms were established by filling battery jars with 12 liters of water from Keystone Reservoir. Microcosms were enriched by adding sufficient Ca $(NO_3)_2$ and Na HPO_4 to increase nutrient concentrations to 5 g NO_3-N m^{-3} and 5 g PO_4-P m^{-3} and were illuminated at 257 ft-c by Sylvania Gro-Lux lights. Rates of Pg and Rt obtained by the three methods were significantly different (α = 0.01) within each microcosm and over all microcosms (Fig. 39). The average rate of Pg as

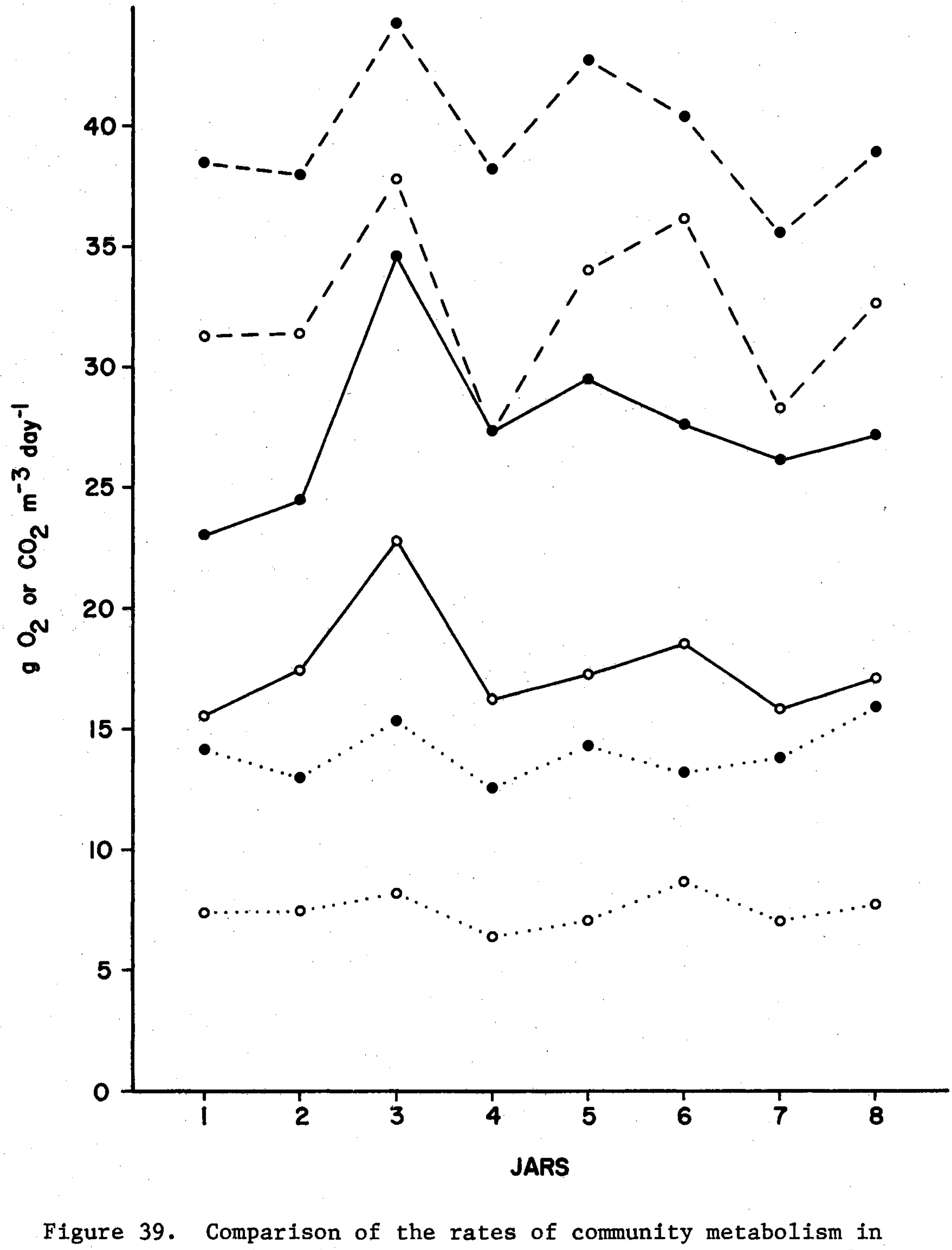

Figure 39. Comparison of the rates of community metabolism in eight laboratory microcosms containing water from Keystone Reservoir as measured by the pH-CO_2 curve method (---), O_2 curve method (———), and light and dark bottle method (····). ● = $\bar{X}$ gross primary productivity, and o = $\bar{X}$ total community respiration (2 replicate measurements per jar).

estimated by the O_2 curve method was equivalent to 0.69 of the pH-CO_2 curve estimate and 1.95 of the L & D bottle estimate. Rt estimated by the O_2 curve method averaged 0.54 of the pH-CO_2 curve estimate and 2.35 of the L & D bottle estimate. A similar pattern of variation in Pg and Rt among jars was obtained with both pH-CO_2 and O_2 curve methods. No significant differences ($\alpha = 0.05$) in Pg and Rt were detected among jars by the L & D bottle method. Free-water methods were more sensitive to differences in rates of metabolism among jars than the bottle method. Bottles apparently inhibited metabolic rates.

Gross Productivity and Community Respiration

Spatial Variation

During 1966-67, 176 oxygen curves were obtained from the Cimarron arm of Keystone Reservoir. On 11 dates, spaced at 2 to 8 week intervals, measurements were made simultaneously at four sampling locations. All measurements were made on clear days so that temporal comparisons could be made. Rates of Pg and Rt per unit area increased downstream (Table XXXVIII). Pg exceeded Rt at Stations I and II, but Rt exceeded Pg at Stations III and IV. A maximum annual mean Pn of 5.06 g O_2 m^{-2} day^{-1} was obtained at Station II. The decrease in Pn from -2.42 to -5.03 g O_2 m^{-2} day^{-1} between Stations III and IV probably was due to an increase in the relation between total depth and EZ depth from 6.26 at Station III to 6.74 at Station IV. The relations between total depth and EZ depth at Stations I and II were 3.27 and 5.40, respectively. Pg/Rt ratios indicated that on the average autotrophic conditions existed at Stations I and II, and heterotrophic conditions existed at Stations III and IV (Table XXXVIII).

TABLE XXXVIII

ANNUAL MEANS OF COMMUNITY METABOLISM (g O_2 m^{-2} day^{-1}) IN KEYSTONE RESERVOIR DURING 1966-67

Parameter	Stations I $\bar{X} \pm S$		Stations II $\bar{X} \pm S$		Stations III $\bar{X} \pm S$		Stations IV $\bar{X} \pm S$
Pg	11.34 ± 0.31	***	27.38 ± 1.17	***	38.63 ± 1.28	**	49.09 ± 4.59
Rt	11.04 ± 0.19	***	22.32 ± 0.96	***	41.04 ± 2.19	*	54.12 ± 6.31
Pn	0.30 ± 0.38	***	5.06 ± 0.24	***	-2.42 ± 1.10	**	-5.03 ± 2.05
Pg/Rt	1.03 ± 0.10	⊛	1.23 ± 0.08	*	0.94 ± 0.12		0.91 ± 0.01

Asterisks indicate significant differences between means. *** ($\alpha = 0.01$), ** ($\alpha = 0.05$), * ($\alpha = 0.10$), ⊛ ($\alpha = 0.15$).

In deep waters, examination of area-based estimates of Pg and Rt often results in false conclusions about spatial variations in the rate of metabolism. Depth-weighted annual means of community metabolism (Table XXXIX) show a strikingly different spatial variation than area-based estimates (Table XXVIII). The average rate of Pg per m^3 of EZ was highest at Station I (21.81 g O_2 m^{-3} day^{-1}) and increased from a minimum of 17.01 g O_2 m^{-3} day^{-1} at Station II to 18.18 g O_2 m^{-3} day^{-1} at Station IV (Table XXXIX). The spatial variation of average Rt m^{-3} was similar to that of Pg with a maximum at Station I and a minimum at Station II. Increases in area-based rates of Pg and Rt downstream primarily were caused by increases in EZ depth.

TABLE XXXIX

DEPTH-WEIGHTED ANNUAL MEANS OF COMMUNITY METABOLISM
IN KEYSTONE RESERVOIR DURING 1966-67

	Stations			
Parameters	I	II	III	IV
$\bar{X}$ Pg (g O_2 m^{-3} of EZ day^{-1})	21.81	17.01	17.17	18.18
$\bar{X}$ depth of EZ (m)	0.52	1.61	2.25	2.70
$\bar{X}$ Rt (g O_2 m^{-3} day^{-1})	6.49	2.57	2.91	2.97
$\bar{X}$ depth (m)	1.70	8.70	14.10	18.20

The magnitude of Pg and Rt as measured by the O_2 curve method during 1966-67, greatly exceeded the magnitude of Pg and Rt measured by the L & D bottle method during 1965-66 (Fig. 40). Monthly measurements were made from August 1965 through March 1966. Annual means of Pg ranged from a maximum of 2.3 g O_2 m^{-2} of EZ day^{-1} at Station I to a minimum of 0.7 g O_2 m^{-2} of EZ day^{-1} at Station III, and means of Rt ranged from 1.5 g O_2 m^{-2} of EZ day^{-1} at Station II to 0.6 g O_2 m^{-2} of EZ day^{-1} at Station IV. Inhibition due to enclosing water in bottles was evident, and on numerous occasions zero values of Pg and Rt were obtained. Maximum rates obtained by the L & D bottle method were 4.0 g O_2 m^{-2} of EZ day^{-1} Pg at Station I in January 1966 and 5.1 g O_2 m^{-2} of EZ day^{-1} Rt at Station III in August 1965.

The magnitude of estimates of Pg and Rt by the O_2 curve method during 1966-67 also greatly exceeded estimates of Pg during 1966-67 made by Spangler (1969) using the chlorophyll-light intensity method of Ryther and Yentsch (1957). Annual means of Pg were minimum at Station I (0.592 g C m^{-2} day^{-1}) and maximum at Station III (0.890 g C m^{-2} day^{-1}) (Spangler 1969). Maximum values of approximately 3.0 g C m^{-2} day^{-1} were recorded at Station I in September 1966 and at Station II in January 1967. The relationship between chlorophyll and light intensity was derived from estimates of Pg by bottle methods and possess the same errors due to inhibition as the L & D bottle method.

Temporal Variation

Temporal variations in the magnitude of Pg and Rt were large (Fig. 41 and 42). Patterns of variation at Stations I and II were distinct, while patterns of variation at Stations III and IV were similar.

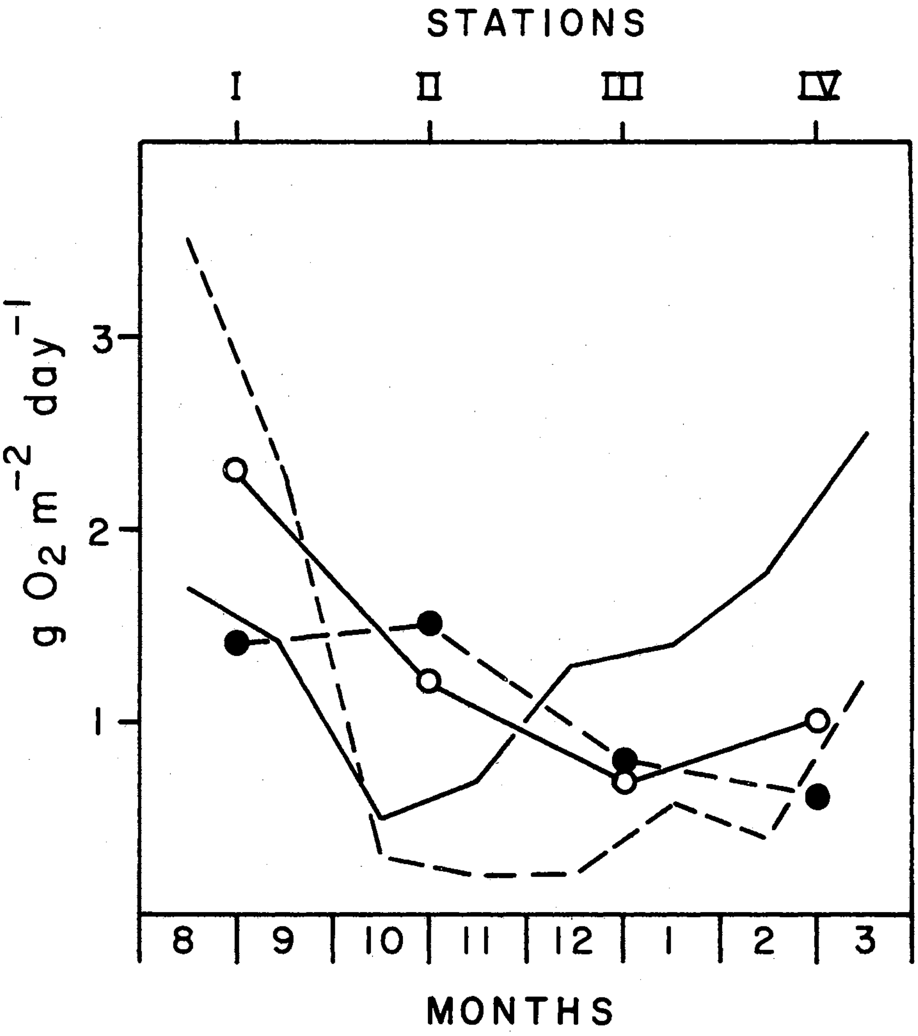

Figure 40. Annual station means (-o-, -●-) and monthly means (——— ,----) of gross productivity (———) and respiration (----) in the euphotic zone of Keystone Reservoir during 1965-66 as measured by the light and dark bottle method

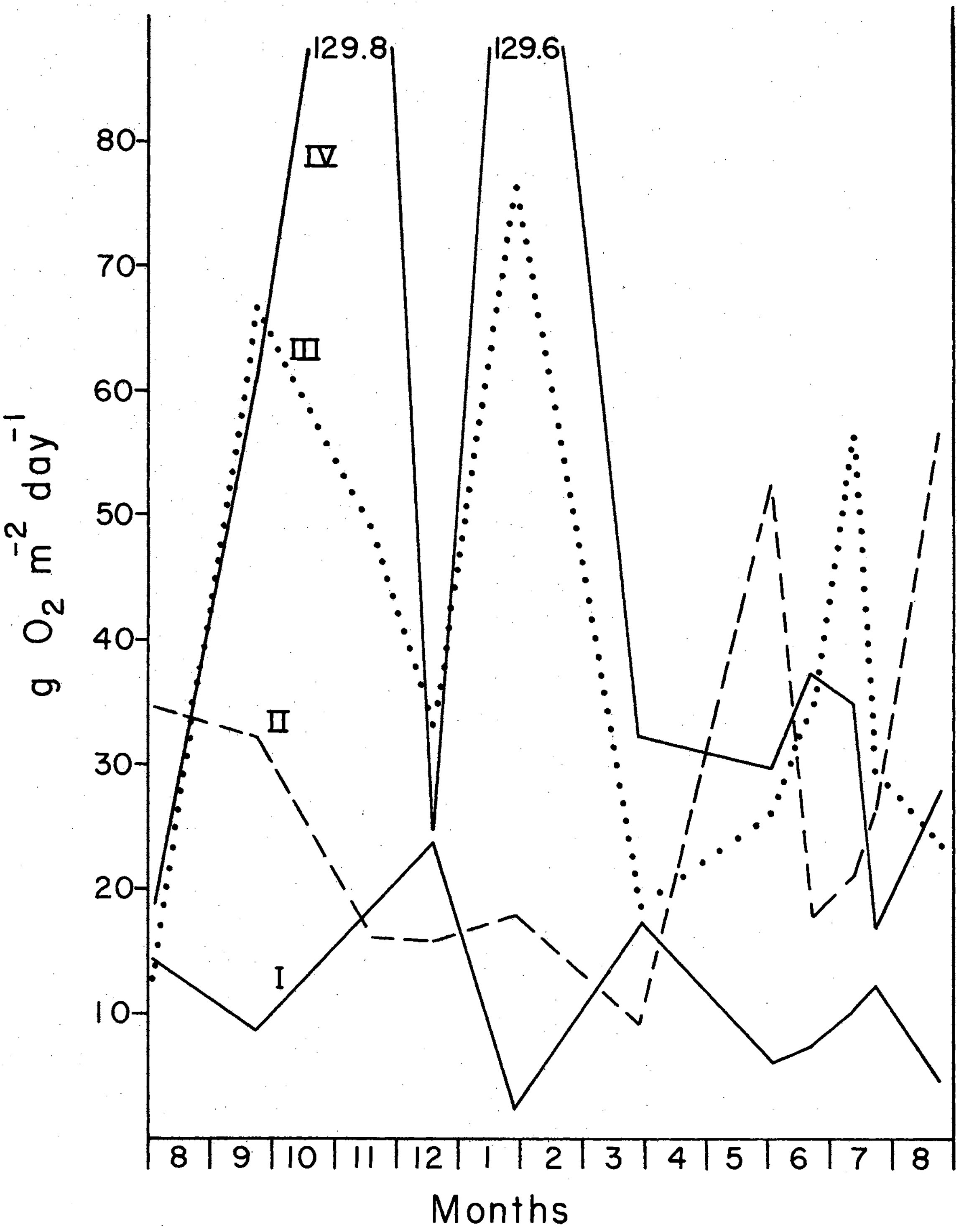

Figure 41. Temporal variation of Pg at stations in the Cimarron arm during 1966-67

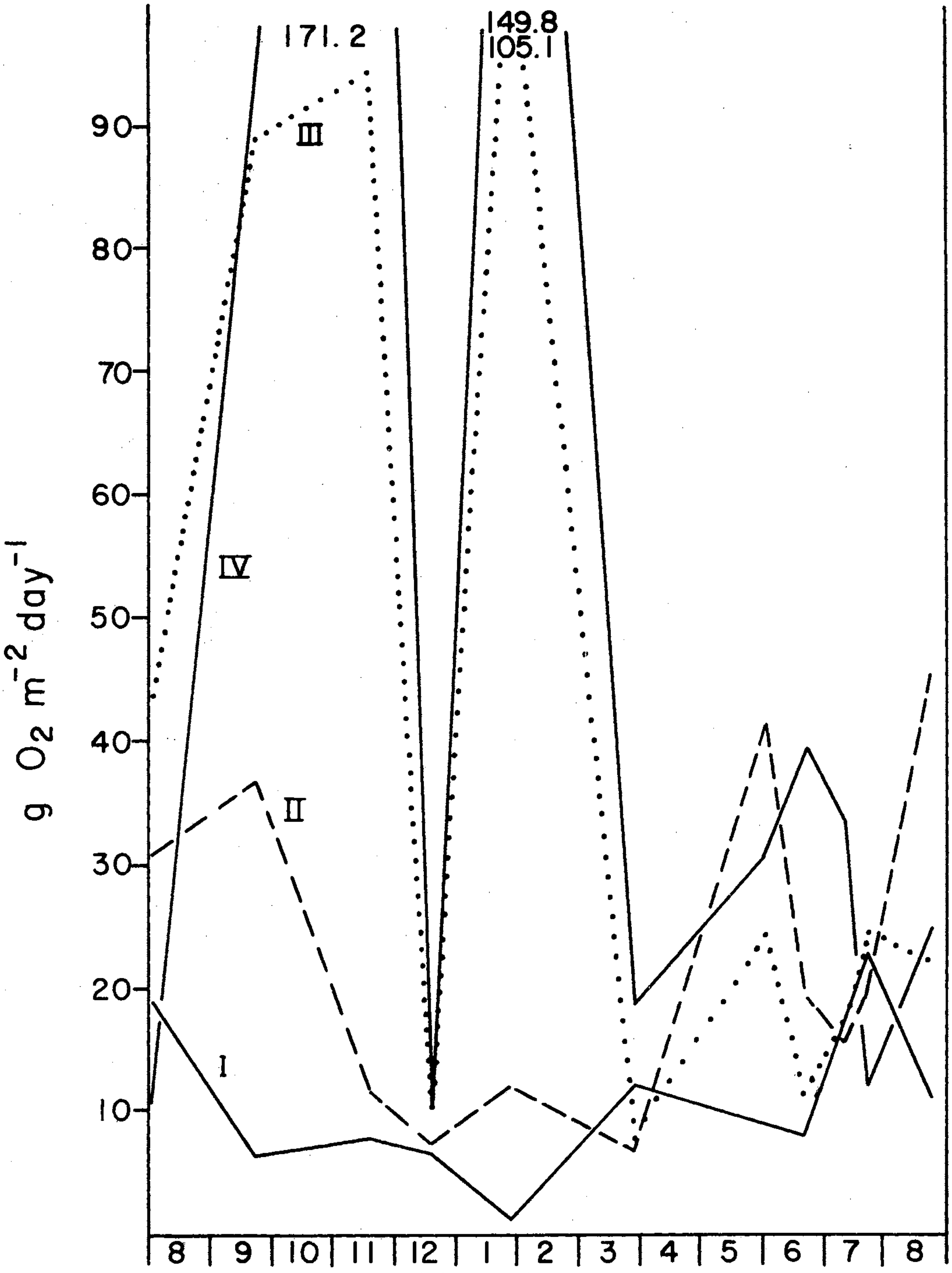

Figure 42. Temporal variation of Rt at stations in the Cimarron arm during 1966-67

Pg varied from a minimum of 2.09 g O_2 m^{-2} day^{-1} at Station I in January 1967 to a maximum of 129.77 g O_2 m^{-2} day^{-1} at Station IV in November 1966. Rt varied from a minimum of 1.12 g O_2 m^{-2} day^{-1} at Station I in January 1967 to a maximum of 171.20 g O_2 m^{-2} day^{-1} at Station IV in November 1966.

Station II exhibited the most definite seasonal pattern of variation of Pg and Rt. Maximum values of Pg and Rt at Station II were recorded in August and September 1966 and in June and August 1967. Pg and Rt were consistently low between November 1966 and March 1967. The flood which occurred during the last half of June 1967 produced a large decrease in both Pg and Rt at Station II. The flood did not noticeably affect Pg at Station I.

Peaks in Pg occurred in September 1966 and January and July 1967 at Station III and in November 1966 and January 1967 at Station IV (Fig. 41). Minimum values of Pg were recorded in August and December 1966 and March and August 1967 at Station III and in August and December 1966 and July 1967 at Station IV (Fig. 41). Increases and decreases in Pg at Stations III and IV generally were accompanied by similar increases and decreases in Rt (Fig. 42). A notable exception occurred at Station III, when Pg decreased significantly between September and November 1966 while Rt increased. Flood waters which entered the reservoir during June 1967 may have caused the decreases in Pg at Stations III and IV during the first half of July (Fig. 41). The influence of flooding was also suggested by a large decrease in Rt at Station IV during July 1967, but Rt increased at Station III during the same period of time (Fig. 42).

High values of Pg and Rt at Stations III and IV in November 1966 and January 1967 probably are valid. O_2 curves for these dates followed the expected pattern, but the magnitude of change was great. The oxygen content of the water column at Station IV varied from a minimum of 127.9 g O_2 m^{-2} at 4.7 hr to a maximum of 173.1 g O_2 m^{-2} at 22.0 hr in November 1966 and from a minimum of 188.5 g O_2 m^{-2} at 4.4 hr to a maximum of 244.2 g O_2 m^{-2} at 20.2 hr in January 1967. Water temperatures (5.5 C) in January 1967 were at the lower limit of the acceptable range for the galvanic cell oxygen analyzer, but in November 1966 water temperatures (13.5 C) were well above the lower limit.

In an attempt to explain high metabolic rates which occurred at relatively low light intensities during September and November 1966 and January 1967, plankton samples from the surface waters of Stations III and IV were examined. Species diversity was extremely low. Small green cells showing a definite clumped distribution in gelatinous-like masses were by far the most abundant form in surface samples. The morphology of the cells ranged from small rods approximately 0.5-1.0 μ in diameter and 2.0-3.0 μ in length to small coccoid or spherical cells ranging in diameter from 0.5-3.0 μ. The cells had an appearance similar to that of green sulfur bacteria belonging to the family Chlorobacteriaceae (personal communication from Francis Drouet, Academy of Natural Sciences, Philadelphia). The size and morphology of the cells were not characteristic of any alga common to Oklahoma (personal communication from A. G. Carroll, OSU). Green sulfur bacteria contain bacteriochlorophyll d̲ and a yellow carotenoid pigment and are capable of photosynthesis and chemosynthesis in which inorganic sulfur compounds are the hydrogen donors (Jensen et al. 1964). Photosynthetic sulfur bacteria of the genus Chlorobium have been reported to be sufficiently abundant to impart a green color to the water of several lakes (Manning and Juday 1941, Newcombe and Slater 1950, and Czeczuga 1965). Since water apparently does not act as a hydrogen donor in bacterial photosynthesis (Gest et al. 1963, Pfennig 1967), sulfur bacteria could not be responsible for the high rates of community metabolism measured by the O_2 curve method. The only evidence found in a review of the literature that oxygen is liberated by bacterial photosynthesis was reported by Godniew and Winberg (1951) (Czeczuga 1965). Godniew and Winberg (1951) stated that green bacteria which were abundant in sewage pools contained chlorophyll a and b in similar proportions to those of higher plants and gave off oxygen in the process of photosynthesis (Czeczuga 1965). Most sulfur bacteria are extremely sensitive to high concentrations of dissolved oxygen and probably could not exist in the surface waters of Keystone Reservoir during the winter (personal communication from E. T. Gaudy, OSU).

Available evidence indicates that the small cells which were abundant in Keystone during the winter of 1966-67 were not sensitive to high concentrations of oxygen and had a high rate of metabolism in which oxygen was involved. Green, unidentified "μ-cells" also were the predominant form during the winter of 1968-69 (personal communication from D. W. Toetz, OSU).

A relationship between the magnitude of Pg and Rt and the trophic state of the community existed (Fig. 43). When Pg and Rt were high, Pg/Rt ratios were low. When Pg and Rt were low, Pg/Rt ratios were high. A notable exception existed at Station III during June and July 1967 when a peak in Pg was accompanied by high Pg/Rt ratios. Extremely

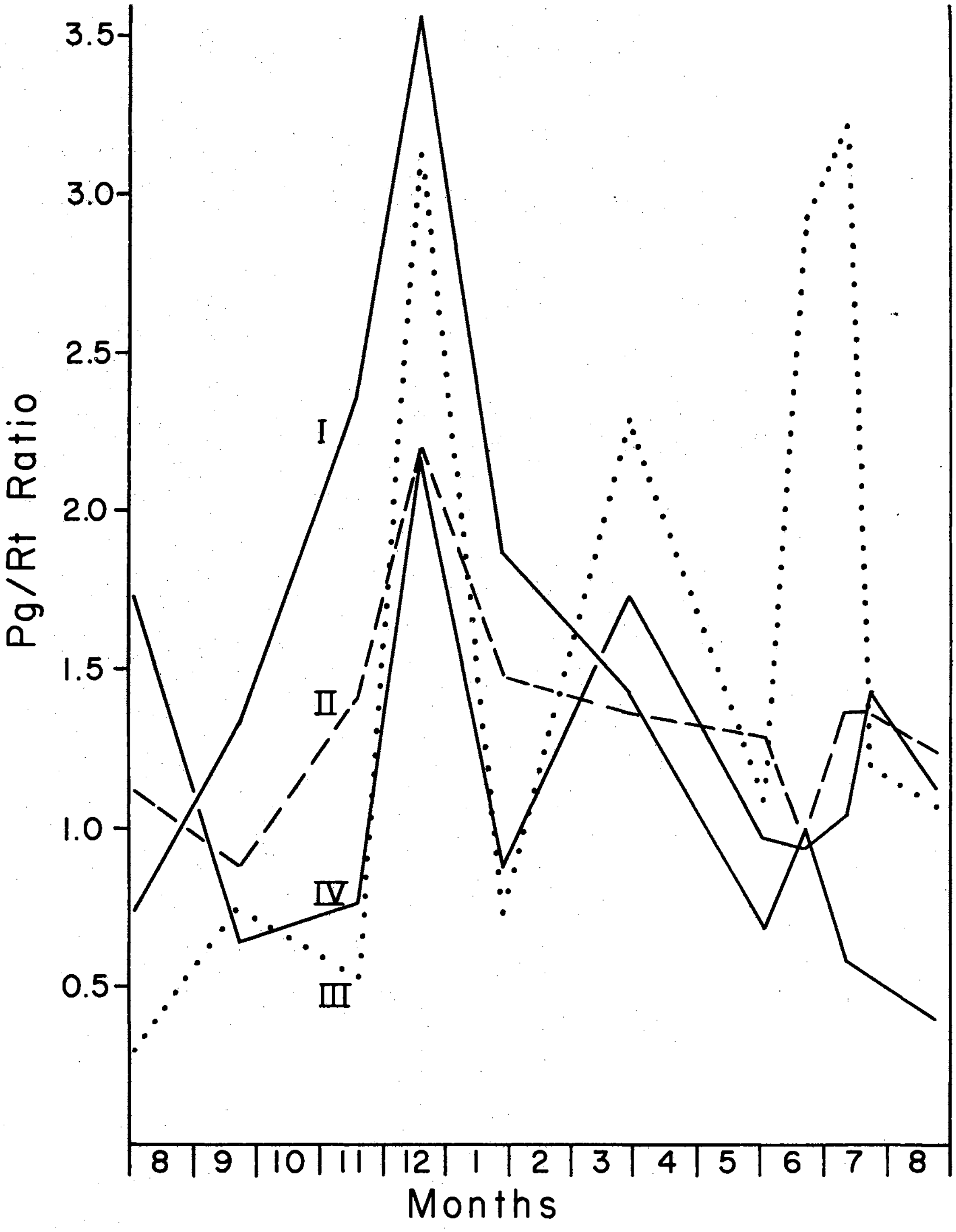

Figure 43. Temporal variation of Pg/Rt ratios at stations in the Cimarron arm during 1966-67

autotrophic conditions existed at all stations in December 1966 when rates of community metabolism were low (Fig. 43). Low Pg/Rt values in November and January 1967 were associated with heterotrophic conditions during high rates of community metabolism at Stations III and IV.

Comparison With Other Waters

Rates of community metabolism in Keystone Reservoir during 1966-67 were within the range of rates estimated by O_2 and pH-CO_2 curve methods for other waters (Table XL). Metabolic rates in Keystone exceeded the maximum rates obtained by ^{14}C and L & D bottle methods in other waters.

When a consideration of water depth is made, the highest rates of community metabolism were obtained by O_2 curve analyses of oxygen data of George (1961) for two small, shallow ponds in Delhi, India (Table XL). Roshanara Garden Tank is a small pond with an area of 24.3 x 10^3 m^2 and an average depth of 1.1 m (George 1961). The sides of the pond and an island in the center of the pond support a luxuriant growth of palm trees that shade the water surface except when the sun is at a vertical (George 1961). A permanent bloom of Microcystis aeruginosa exists. During 21 June 1959, the concentration of dissolved oxygen increased from a minimum of 0.1 g O_2 m^{-3} at 6.00 hr to a maximum of 28.2 g O_2 m^{-3} at 15.00 hr, and oxygen saturation increased from 1.3 to 405.8% (George 1961). This change in O_2 concentration resulted in a Pg of 52.1 g O_2 m^{-2} day^{-1} and an Rt of 41.7 g O_2 m^{-2} day^{-1} (Table XL). The O_2 curve analysis of data from Roshanara Garden Tank is presented as an example of program output in the Appendix. High rates of community metabolism were also obtained for Naini Lake, India which has a mean depth of 0.9 m. The only other rates of similar magnitude for

TABLE XL

COMPARISON OF RATES OF COMMUNITY METABOLISM OF KEYSTONE RESERVOIR AND OTHER WATERS

Water Body	Reference	Method	Type of Data	$g\ O_2\ m^{-2}\ day^{-1}$	
				Pg	Rt
Keystone Reservoir, Oklahoma	Present study	O_2 curve	Annual $\bar{X}$ (n=33) Station I	11.3	11.0
			Station II	27.4	22.3
			Station III	38.6	41.0
			Station IV	49.1	54.1
Roshanara Garden* Tank, India	Present study using data of George (1961)	O_2 curve	6/21/59 (n=1)	52.1	41.7
Naini Lake, India	"	O_2 curve	5/10/59 (n=1)	29.5	46.0
Kadel Pond, Florida*	Present study using data of Kehde (1967)	O_2 curve	Winter $\bar{X}$ (n=6)	8.3	25.8
Corpus Christi Harbor, Texas	Odum (1960)	O_2 curve	7/13/59 (n=1)	31.0	51.0
Rockport and Boffin Bays, Texas	Park et al. (1958)	$pH-CO_2$ curve	Summer $\bar{X}$	41.2	
Western Lake Erie	Verduin (1960, 1967)	$pH-CO_2$ curve	Summer $\bar{X}$	31.7	
Roanoke Rapids Reservoir	Hull (1965)	L&D bottles	$g\ m^{-2}$ of euphotic zone	4.2	2.6
Ashtabula Reservoir, North Dakota	Peterka (1968)	L&D bottles	Annual $\bar{X}$	8.6	3.4
Sylvan Lake, Indiana	Wetzel (1966)	Carbon-14	Annual $\bar{X}$	7.2	
Lago Pond, Georgia	Welch (1968)	O_2 curve	Annual $\bar{X}$	5.3	7.6
Oil Refinery Effluent Holding Ponds, Oklahoma	Copeland (1963)	O_2 curve	Maximum	29.2	50.5
Skeleton Creek, Oklahoma	Baumgardner (1966)	O_2 curve	Annual $\bar{X}$ of O_2 Sag Zone	13.6	33.5
Blue River, Oklahoma	Duffer and Dorris (1966)	O_2 curve	Annual $\bar{X}$ for granite reach	21.4	12.6

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*O_2 curve calculations are presented as examples of O_2 curve program output in the Appendix.

waters of similar depth were reported by Copeland (1963) for oil refinery effluent holding ponds and by Baumgardner (1966) for Skeleton Creek, a stream receiving oil refinery and domestic sewage effluents. Rates of community metabolism similar to those of Keystone Reservoir have been reported for polluted, stratified Texas Bays by Park et al. (1958) and Odum (1960) and for Western Lake Erie by Verduin (1960, 1967).

Variation in Community Metabolism During Eight Consecutive Days

Temporal variations in Pg and Rt in Keystone Reservoir indicated that weekly or even daily estimates of community metabolism would be necessary to adequately monitor temporal changes (Fig. 41 and 42). To provide an estimate of daily variation in the rate of community metabolism, O_2 curves were obtained during eight consecutive days of August 1967 at Station III (Table XLI). Pg ranged from a maximum of 29.95 g O_2 m^{-2} day^{-1} on 14 August to a minimum of 15.83 g O^2 m^{-2} day^{-1} on 15 August, and Rt varied from a minimum of 23.23 O_2 m^{-2} day^{-1} on 16 August to a maximum of 35.00 g O_2 m^{-2} day^{-1} on 17 August (Table XLI). The only significant differences ($\alpha = 0.10$) demonstrated among daily estimates of Pg and Rt were between the extremes. During 4 days, estimates of Pg and Rt were made at six substations. No significant differences between the means obtained at the three additional substations and the means obtained at the regular substations were found. The lack of differences between means obtained at two sets of three substations indicated that three substations provided an adequate estimate of the average rate of community metabolism at Station III. Several differences in Pn and Pg/Rt between successive days were found (Table XLI).

Daily variations in metabolic rates were within the range reported for a constant temperature river in Texas (Hannan 1967).

TABLE XLI

VARIATION IN COMMUNITY METABOLISM AT STATION III
IN AUGUST 1967

	$\bar{X}$ g O_2 m^{-2} day^{-1} (3 reps per date)			
Date	Pg	Rt	Pn	Pg/Rt
10 August	16.93	28.09	-11.16	0.60
			*	*
11 August	21.43	24.13	-2.70	0.89
12 August	21.20	25.20	-4.00	0.84
13 August	26.99	30.06	-3.07	0.90
14 August	29.95	31.56	-1.61	0.95
	*		*	*
15 August	15.83	29.73	-13.90	0.53
			*	*
16 August	18.56	23.23	-4.66	0.80
		*	*	*
17 August	23.47	35.00	-11.70	0.67

* indicates significant difference ($\alpha = 0.10$) between means.

Solar Radiation and Efficiency of Pg

Solar radiation on clear days when estimates of community metabolism were made always exceeded monthly averages (Fig. 44). Solar radiation ranged from a minimum of 253 g cal cm^{-2} day^{-1} in December 1966 to

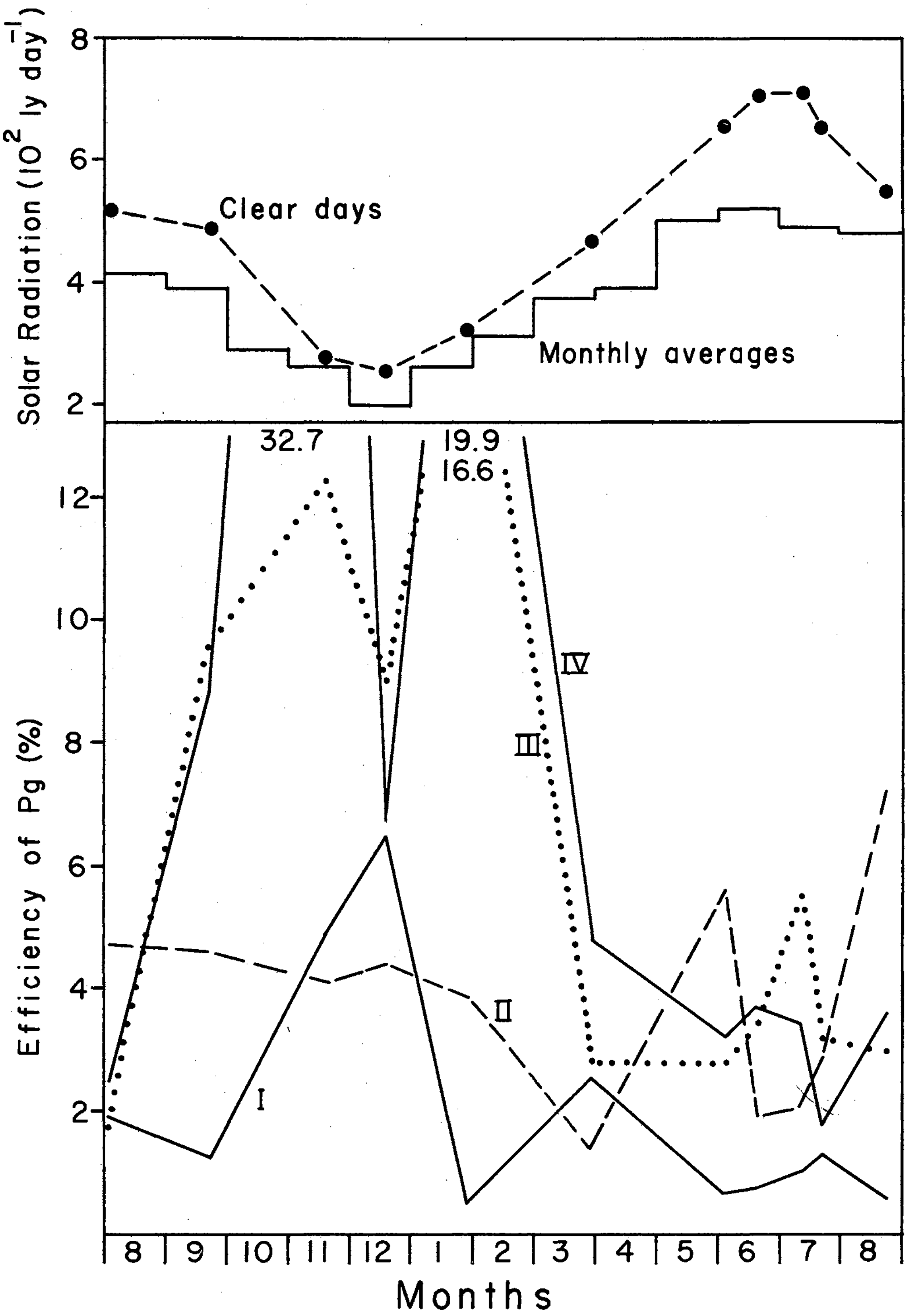

Figure 44. Comparison of solar radiation on sampling dates to monthly means of solar radiation, and spatial and temporal variations of efficiency in the Cimarron arm during 1966-67

a maximum of 658 g cal cm^{-2} day^{-1} in July 1967. No apparent relationship existed between high rates of Pg and Rt and solar radiation. Solar radiation apparently did not limit photosynthesis and no evidence of photo-inhibition due to high light intensities was found. High midday light intensities probably inhibited photosynthesis in the surface water, but the effect was masked by increased metabolism at lower layers of the euphotic zone.

Efficiency of Pg was calculated using solar radiation data by the formula,

$$F = \frac{(3500\ Pg)\ 100}{10{,}000 \times S} \quad \text{(modified from Oswald et al. 1957)}$$

where, F = percent efficiency,

Pg = g O_2 m^{-2} day^{-1},

S = effective solar radiation in g cal cm^{-2} day^{-1}, and

10,000 is a factor to convert cm^2 to m^2.

A value of 50% of total solar radiation was considered to fall within the range of photosynthetically effective light (Edmondson 1955, Ryther 1956b).

Efficiencies ranged from a minimum of 0.52% at Station I in January 1967 to a maximum of 32.68% at Station IV in November 1966 (Fig. 44). Annual means of efficiency were 1.97% for Station I, 3.87% for Station II, 6.35% for Station III, and 8.23% for Station IV. Maximum efficiencies at Stations I, III, and IV occurred on days of low solar radiation. Bauer (1957) concluded that there is an inverse relationship between solar radiation and efficiency, and that efficiency is also dependent on the quantity and quality of photosynthetic pigments. The transparency of water also determines the efficiency of light utilization (Comita and Edmondson 1953).

Vinberg (1960) stated that phytoplankton can use only about 4% of the total energy of solar radiation under the most favorable conditions. Using 100% of solar radiation to calculate efficiency, the maximum efficiency found in Keystone Reservoir would exceed the maximum reported by Vinberg (1960) by a factor of 4. Vinberg's conclusion was based on L & D bottle data and probably is not valid.

Efficiencies of Pg found in Keystone Reservoir were in the upper range of those reported in the literature. Efficiencies varied from 0.5 to 10% for 11 Florida springs and a turtle grass community (Odum 1957). Oswald et al. (1957) reported efficiencies ranging from 1 to 10% for sewage oxidation ponds. Lower efficiencies were reported in Skeleton Creek, Oklahoma, 0.5 to 6.4% (Baumgardner 1966); in San Marcos River, Texas, 0.2 to 4.8% (Hannan 1967); in Blue River, Oklahoma, 0.2 to 5.4% (Duffer and Dorris 1966); and in oil refinery effluent holding ponds, 0 to 3.9% (Copeland 1963).

The relation of Pg, solar radiation, and efficiency during eight consecutive days at Station III in August 1967 indicated an inverse relationship between efficiency and solar radiation and a direct relationship between efficiency and Pg (Fig. 45). Similar results have been reported by Odum and Hoskin (1958), Copeland (1963), Butler (1964), Duffer and Dorris (1966), and Hannan (1967).

Relation of Community Metabolism to Chlorophyll *a* and Biomass

The relation of community metabolism to chlorophyll *a* and biomass was investigated in an effort to explain spatial and temporal variations in metabolic rates. Variations in solar radiation apparently

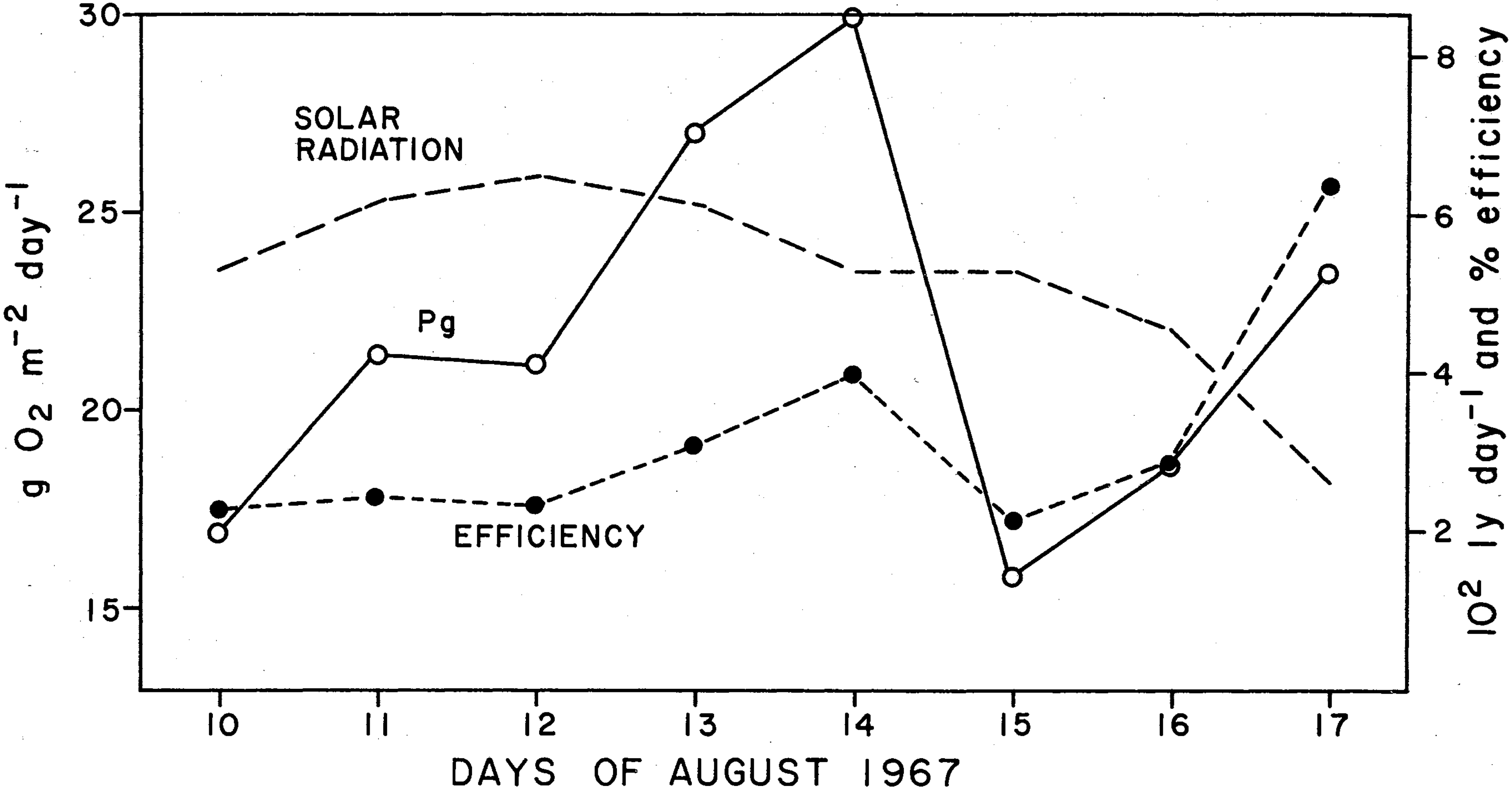

Figure 45. Relation of Pg, solar radiation, and efficiency at Station III in August 1967

were not the controlling factor in temporal variations of Pg and Rt. Nutrients probably were not limiting and probably did not contribute to variations in Pg and Rt. Spatial variations were caused by differences in light penetration, but spatial variations in depth-weighted means of Pg and Rt indicated that other factors were also influencing metabolic rates (Table XXXIX). On some dates, correlations between Pg and chlorophyll a concentrations and Rt and biomass concentrations were evident, but at other times apparently no relationship existed (Fig. 46, Fig. 47). A notable lack of correlation between Pg and chlorophyll a occurred at Stations III and IV in September and November 1966 and January 1967 (Fig. 46).

Direct relationships between Pg and chlorophyll a and between Rt and biomass existed between Stations I and II, but inverse relationships existed among Stations II, III, and IV (Fig. 48). Concentrations of chlorophyll a in the EZ decreased between Stations II, III, and IV while Pg (g O_2 m^{-3} of EZ day^{-1}) increased. Average biomass concentrations in the water column decreased between Stations II, III, and IV while Rt (g O_2 m^{-3} day^{-1}) increased. According to the inverse size metabolism law, the relations between community structure and function at Stations II, III, and IV indicate that the average size of organisms present in the communities decreased downstream. A relation between average organism size and rate of community metabolism is suggested by relatively high values of Rt occurring at relatively low concentrations of biomass at Stations III and IV during September and November 1966 and January 1967 when species diversity was extremely low and small unidentified μ cells were abundant (Fig. 49). Although the scatter of points was large, especially those from Station I, a relationship

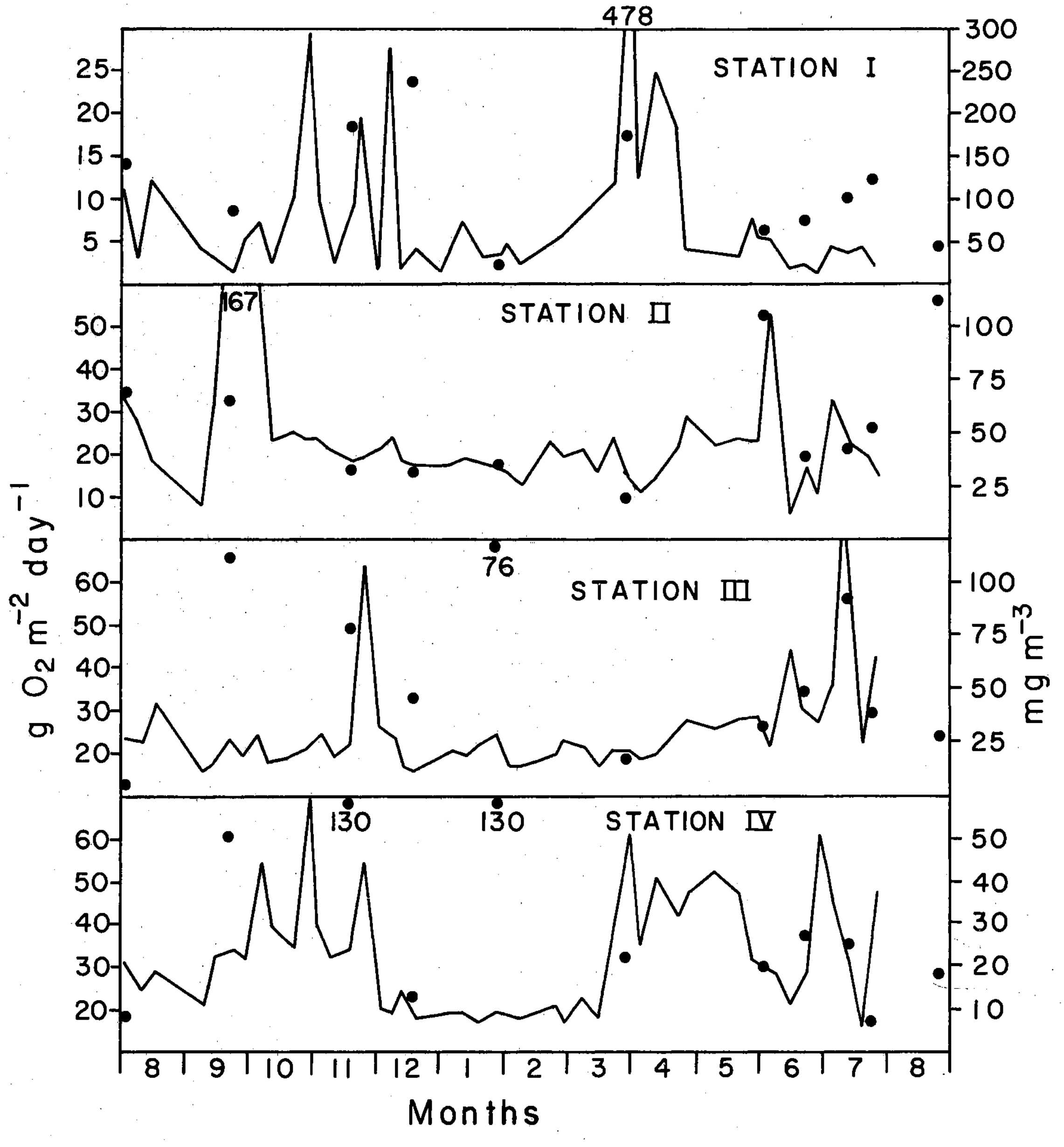

Figure 46. Temporal variation of concentrations of chlorophyll a (———) in surface water and Pg (●) in the Cimarron arm during 1966-67

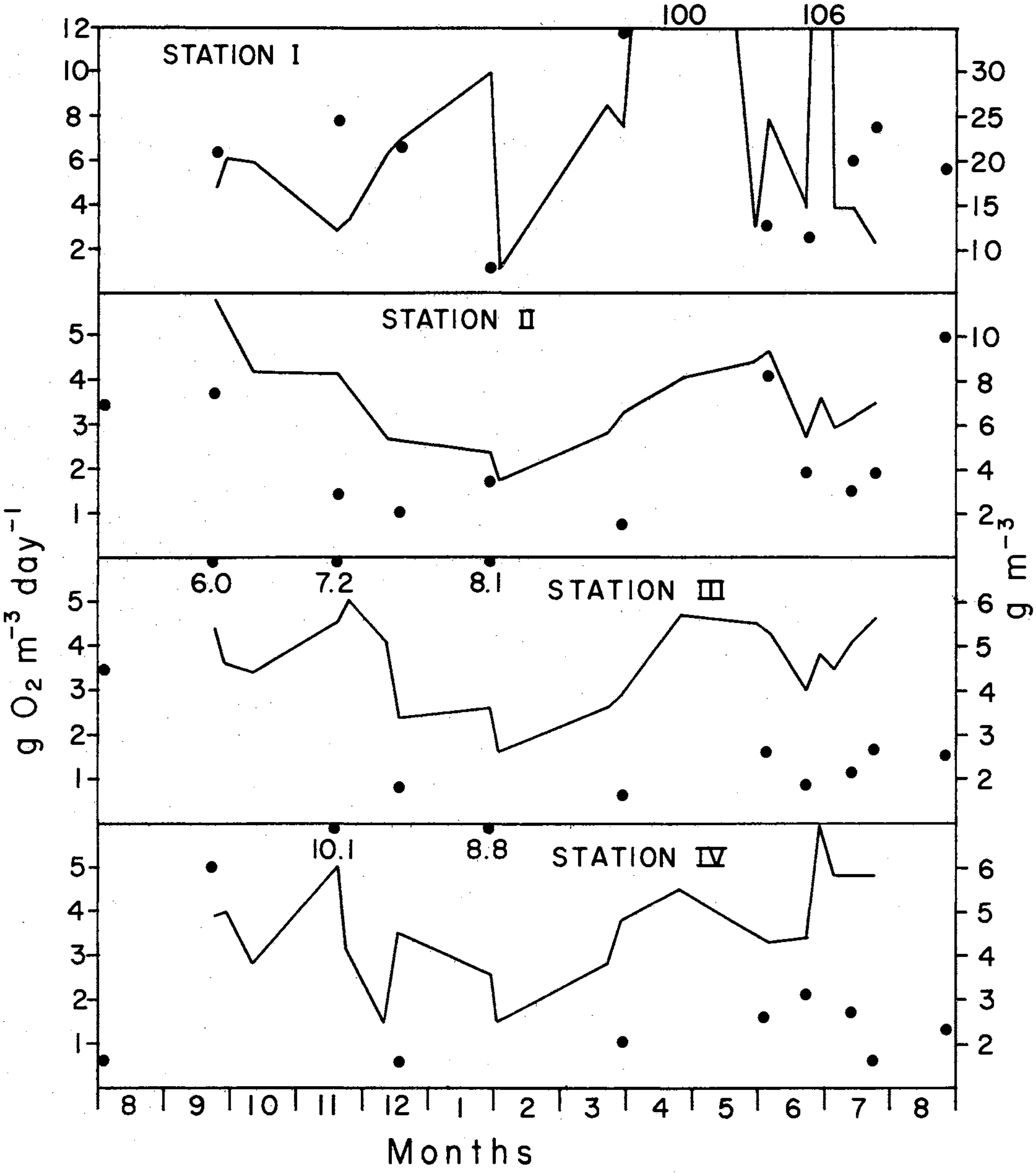

Figure 47. Temporal variation of $\bar{\bar{X}}$ concentrations of biomass (———) and $\bar{X}$ rates of respiration (●) in the Cimarron arm during 1966-67

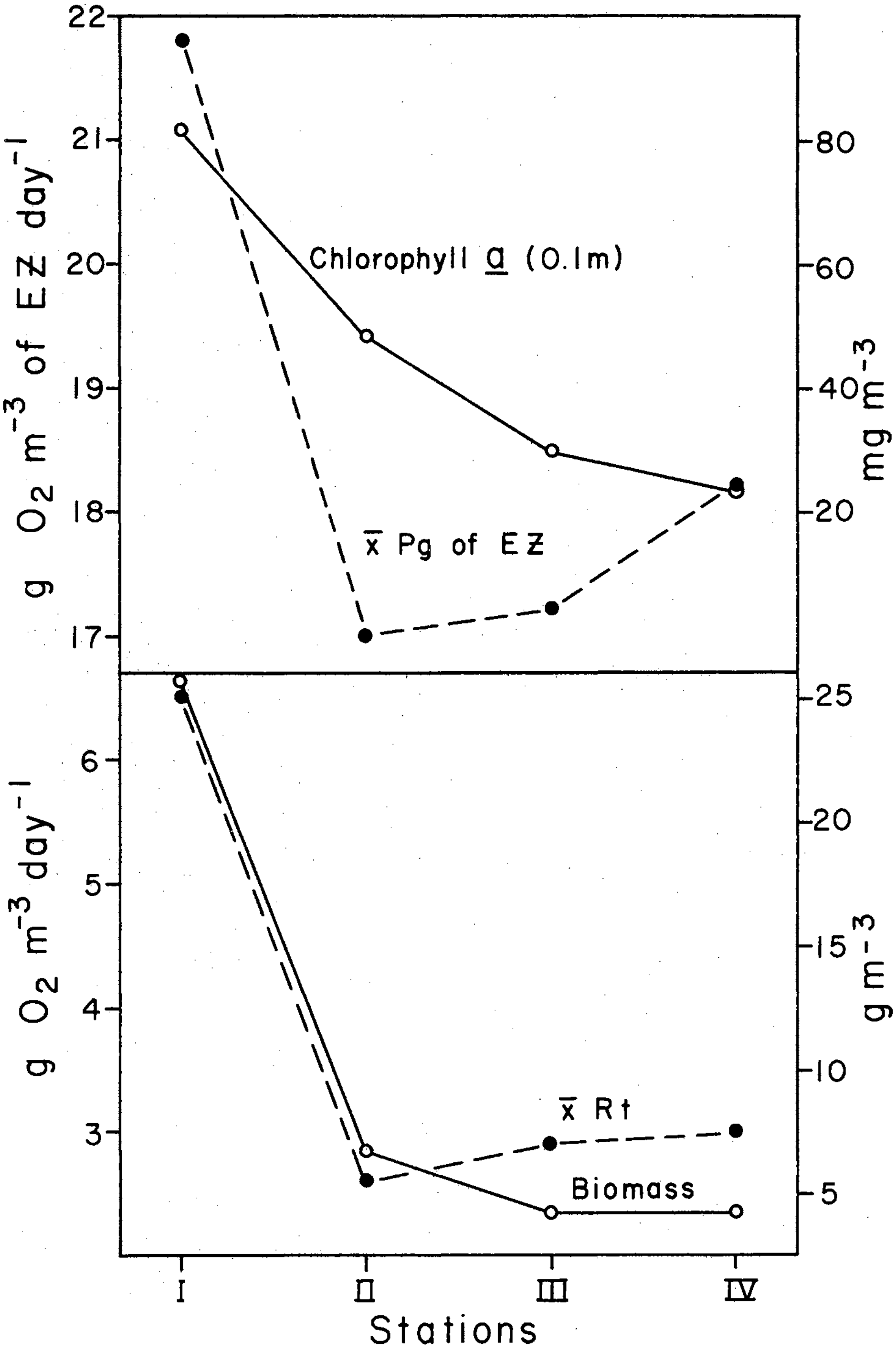

Figure 48. Spatial variations in annual mean plankton structure and function in the Cimarron arm during 1966-67

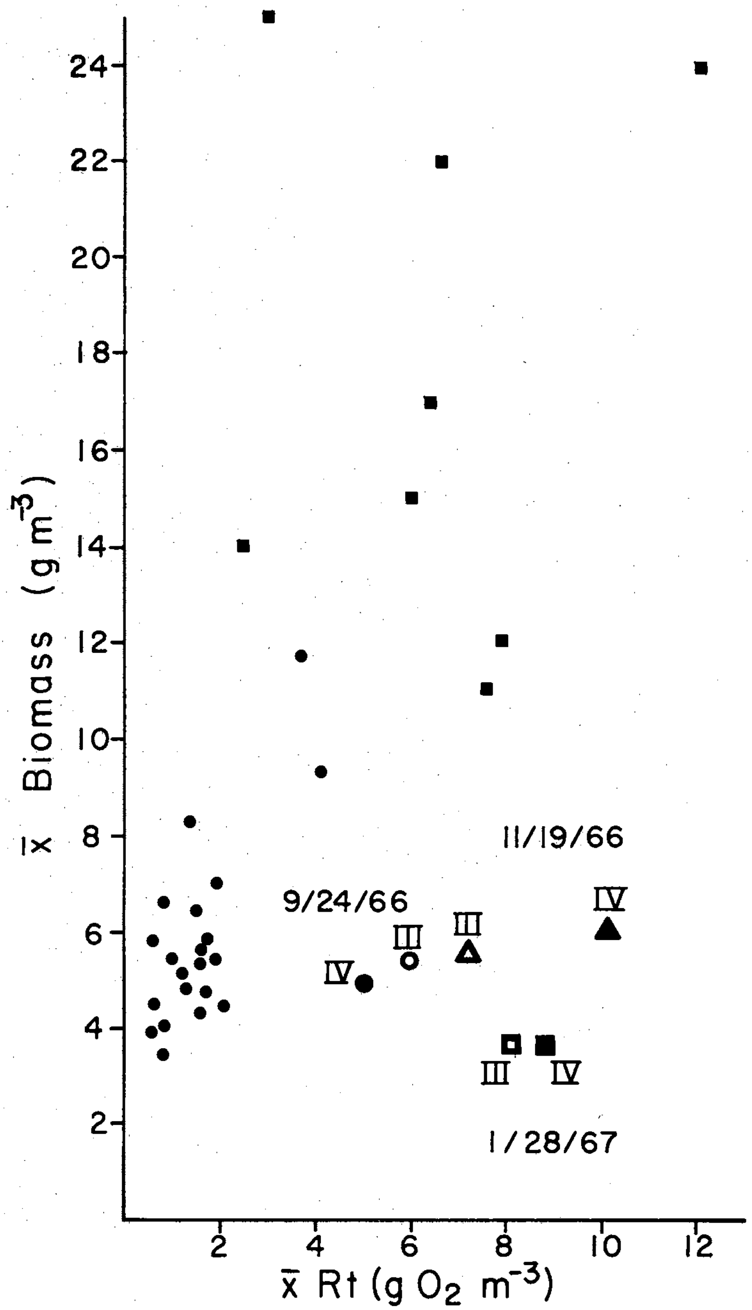

Figure 49. Relation of community respiration to biomass concentration. Large points represent data when unidentified μ cells were the dominant form. ■ = data from Station I, ● = data from Stations II, III, and IV.

between Rt and biomass apparently existed. A linear correlation between biomass and Rt of 0.75 was obtained (95% C.I. = $0.47 < \rho < 0.88$). The large variation in the relationship between Rt and biomass at Station I probably was caused by errors in biomass determinations. Biomass was estimated by gravimetric analyses of ash-free dry weight, and significant errors occurred when clay turbidity was high (Spangler 1969). Clay particles retained moisture in oven-dried samples but lost the moisture on ignition.

Bacteria were always abundant in plankton samples collected at Station I. Heterotrophic forms were dominant but probably did not constitute a large percentage of the biomass. Diatoms were by far the most abundant phytoplankter and probably made a significantly greater contribution to biomass than did bacteria. In November 1966, an analysis of phytoplankton community structure at Station I was made using a Sedgewick-Rafter counting chamber and the strip-count method. Based on examination of six slides (600 individuals), there was an average concentration of 13.98×10^6 organisms per liter. Diatoms composed 83% of the total number of individuals. The next most abundant photoplankter, Selenastrum, composed less than 6% of the total number of individuals. The phytoplankton community had a species diversity ($\bar{d}$) of 2.02 using Shannon's formula (Patten 1962).

Greater seasonal changes in plankton occurred at Stations II, III, and IV than at Station I. In general, solitary Chlorophyta were the most abundant form of phytoplankton, with diatoms and bluegreens in lesser abundance. The bluegreens, Oscillatoria and Merismopedia, were most abundant in October and November 1966 and in August 1967. The observed peak in bluegreen algae during late summer and fall follows the expected pattern of seasonal succession of diatoms, green algae, and bluegreen algae (Fogg 1965). High concentrations of chlorophyll b in the fall also indicated an abundance of bluegreen algae (Spangler 1969). Diatoms were most abundant at Stations II, III, and IV in the spring. A large bloom in desmids, primarily Scenedesmus, was observed at all stations during May and early June 1967. The flood during June 1967 practically eliminated desmids from Stations I and II, but desmids remained at Stations III and IV throughout June 1967. Green μ cells were common to abundant in the surface waters of Station IV throughout 1966-67, except in October 1966 and June 1967. In January 1967, green μ cells were extremely abundant in the surface waters of Stations III and IV, and phytoplankton were extremely scarce. The greater influence of small organisms with high metabolic rates at the deeper stations is indicated by increases in Rt/biomass ratios (Table XLII). The Rt/biomass ratio was lowest at Station I and highest at Station IV, with the most significant increase occurring between Stations II and III.

Margalef (1958) stated that as succession proceeds Pn decreases at a greater rate than biomass increases; therefore, the Pn/b ratio decreases. In marine communities the Pn/b ratio varied from 0.5 to 2.0 during the first stage of succession, from 0.2 to 0.5 in the second stage of succession, and was less than 0.2 in the third state of succession (Margalef 1958). To examine the relationship between Pn and biomass in Keystone Reservoir it was necessary to estimate the Pn of the EZ since no production occurred below the EZ, and the relationship between depth of EZ and maximum depth would influence the Pn/b ratio. To estimate Pn of the EZ, the average Rt m^{-3} of EZ was estimated from O_2 curve analyses of O_2 changes at 0.5 m of depth. The average rate of

Rt m^{-3} of EZ was 1.5 times the mean Rt of the water column at Station I, 3.0 times mean Rt of the water column at Station II, 4.0 times mean Rt of the water column at Station III, and 4.5 times mean Rt of the water column at Station IV. These values must be considered as approximations since errors in O_2 curve analyses of surface waters probably resulted from vertical transport of O_2.

TABLE XLII

VARIATION OF STRUCTURAL AND FUNCTIONAL PARAMETERS AMONG STATIONS IN THE CIMARRON ARM

	Stations			
Parameter	I	II	III	IV
Pn (g O_2 m^{-2} of EZ day^{-1})*	16.75	14.97	12.49	13.02
Biomass (g m^{-2} of EZ)	14.21	13.68	12.33	13.42
Pn/Biomass	1.18	1.09	1.01	0.97
Rt (g O_2 m^{-3} day^{-1})	6.49	2.57	2.91	2.97
Biomass (g m^{-3})	25.75	6.62	4.33	4.29
Rt/Biomass	0.25	0.39	0.67	0.69

*Pn per m^2 of EZ was estimated by the relationship, Pn m^{-2} of EZ = Pg m^{-2} - Rt m^{-2} of EZ, where Rt m^{-2} of EZ = ($\bar{X}$ Rt m^{-3} of EZ) (EZ in m). $\bar{X}$ Rt m^{-3} of EZ was estimated from O_2 curve analyses of O_2 changes at 0.5 m of depth.

Pn/b ratios decreased between Stations I and IV, and ratios at all stations were characteristic of the first stage of succession proposed by Margalef. Immaturity of the reservoir ecosystem was also suggested by large temporal variations in community structure and function and by high rates of community metabolism. Wilhm and Long (1969) found that Pn/b ratios in laboratory microcosms were characteristic of the third stage of succession, and no definite relationship between Pn/b ratios and nutrient concentrations was observed.

CHAPTER VII

OXYGEN BALANCE OF THE CIMARRON ARM

Biochemical and Chemical Oxygen Demand

Spatial and Temporal Variation

Average concentrations of 5-day and 20-day BOD and COD decreased downstream with the greatest decrease occurring between Stations I and II (Table XLIII). The BOD reaction constant k, which is an indication of the biodegradability of organic matter, increased between Stations I and II and decreased between Stations II and IV (Table XLIII). Lowest BOD k values would be expected at Station IV since chemical compounds which are easily biodegradable would be oxidized in the upper reaches of the reservoir, and the relative proportion of organic compounds resistent to biochemical oxidation would increase downstream. The cause of the significant increase in BOD k at Station II is not known. No significant differences in average concentrations of BOD and COD or in BOD k values were found among depths within stations.

Since BOD and COD parameters are estimates of potential oxygen demand rather than exerted oxygen demand, highest BOD and COD concentrations would be expected when conditions for oxidation were most unfavorable. Temporal variation in BOD and COD concentrations followed the expected pattern, with highest concentrations occurring in cold months and lowest concentrations occurring in warm months (Table XLIII).

TABLE XLIII

SPATIAL AND TEMPORAL VARIATION OF MEAN CONCENTRATIONS OF BOD AND COD AND MEAN BOD REACTION CONSTANTS IN CIMARRON ARM DURING 1966-67

	5-day BOD	20-day BOD	BOD k	COD
Station I	3.8	11.2	0.035	176
	*	*	*	*
Station II	2.5	6.6	0.041	46
	*		*	
Station III	1.4	5.2	0.029	28
Station IV	1.1	4.5	0.026	18
8/1/66	1.4			
9/24/66	2.1	4.7		33
		*		
11/19/66	3.1	7.9	0.042	42
12/17/66	2.8	8.0	0.038	48
		*	*	*
1/28/67	3.6	11.6	0.031	163
		*		*
3/29/67	2.8	9.2	0.028	103
	*		*	*
6/4/67	1.6	7.5	0.019	36
		*		
7/23/67	1.2	4.7	0.026	22
			*	
8/24/67	1.1	3.1	0.042	29

*Indicates significant difference (α = 0.20) between means.

BOD k values generally were higher in winter than in summer, but a significantly higher BOD k value in August 1967 was associated with low BOD concentrations.

Comparison With Other Waters

BOD concentrations in Keystone Reservoir were within the range of concentrations reported for other reservoirs and were considerably less than BOD concentrations in Skeleton Creek, a stream receiving oil refinery and domestic sewage effluents (Table XLIV). COD concentrations in Keystone Reservoir generally were higher than values reported for other reservoirs, and COD concentrations at Station I exceeded concentrations found in Skeleton Creek by Baumgardner (1966). The higher ratios of COD to BOD in Keystone Reservoir than in Skeleton Creek indicated an increase in the relative concentration of chemical compounds which are resistant to biochemical oxidation.

Total Oxygen Content and Potential Oxygen Demand

Total oxygen content of the Cimarron arm was calculated by determining the average oxygen concentration at each meter of depth, multiplying this average by the volume of water contained in the 1-m interval, and summing the products. Total potential oxygen demand of the Cimarron arm was calculated in a similar manner using average 20-day BOD concentrations at each meter of depth. Oxygen content and potential oxygen demand of the Cimarron arm were lowest during warm months and greatest during cool months in 1966-67 (Fig. 50). Oxygen content exceeded potential oxygen demand on all sampling dates. However, since estimates of oxygen content were made only on clear days, they must be

TABLE XLIV

COMPARISON OF 5-DAY BOD AND COD CONCENTRATIONS (g O_2 m^{-3}) IN KEYSTONE RESERVOIR AND OTHER WATERS

Water Body	Reference	Type of Data	5-Day BOD	COD
Keystone Reservoir	Present study	Annual $\bar{X}$, I	3.8	176
		II	2.5	46
		III	1.4	28
		IV	1.1	18
Cherokee Reservoir	Churchill & Nicholas (1967)	Range, June 1966	1.3-3.0	8.7-10.7
Cherokee Reservoir	TVA (1964)	Mean	0.9	
Watts Bar Reservoir	TVA (1967)	Annual $\bar{X}$	1.3	
Chickamauga Reservoir	TVA (1964)	Annual $\bar{X}$	1.4	
Slapy Reservoir, Czech.	Hrbacek (1966)	Annual $\bar{X}$	2.4	31
Klicava Reservoir, Czech.	Straskrabova-Prokesova (1966)	Annual $\bar{X}$	1.7	12
Skeleton Creek, Okla.	Baumgardner (1966)	Range of $\bar{X}$	9.6-21.0	13-135

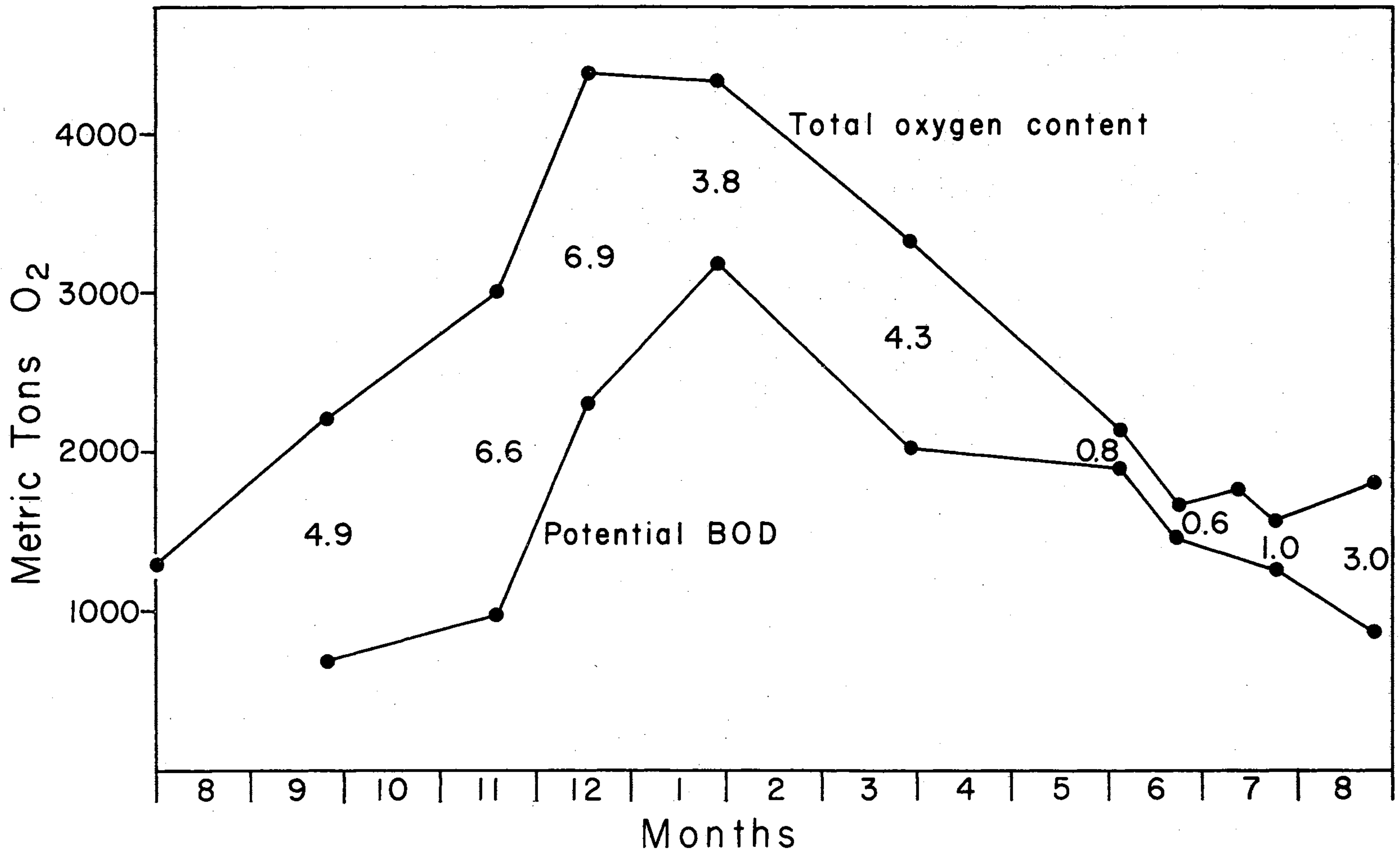

Figure 50. Comparison of total oxygen content and potential oxygen demand of the Cimarron arm on cloudless days during 1966-67. Numbers between lines are the $\bar{X}$ g O_2 m^{-3} of the water mass if the potential oxygen demand was exerted.

considered as maximum values. Potential oxygen demand would not be expected to vary significantly between clear and cloudy days. On some cloudy days potential oxygen demand may have exceeded total oxygen content.

An estimate of the average concentration of dissolved oxygen which would remain after exertion of potential oxygen demand was obtained by dividing the difference between total oxygen content and potential oxygen demand by the volume of the Cimarron arm (Fig. 50). The relationship between oxygen content and potential oxygen demand was most favorable during November and December 1966 when the reservoir would have had more than 6.5 g O_2 m^{-3} if the potential oxygen demand had been exerted. During June, July, and August 1967, exertion of the potential oxygen demand would have reduced average oxygen concentrations below 4 g O_2 m^{-3}.

Daily Oxygen Budgets

Gains in the oxygen content of a reservoir may occur through photosynthetic productivity, atmospheric diffusion, or inflows. Losses may occur by community respiration, diffusion of oxygen out of the water, and reservoir discharge. The oxygen budget of the Cimarron arm was calculated for each sampling date during 1966-67 to estimate the relative importance of the various factors in the oxygen balance of the reservoir and to evaluate the accuracy of the O_2 curve method in predicting the oxygen balance. To estimate the contribution of oxygen by productivity and atmospheric diffusion-in and the oxygen losses by community respiration and diffusion-out, O_2 curve analyses were made of changes in total oxygen content of the Cimarron arm (Fig. 51). Since

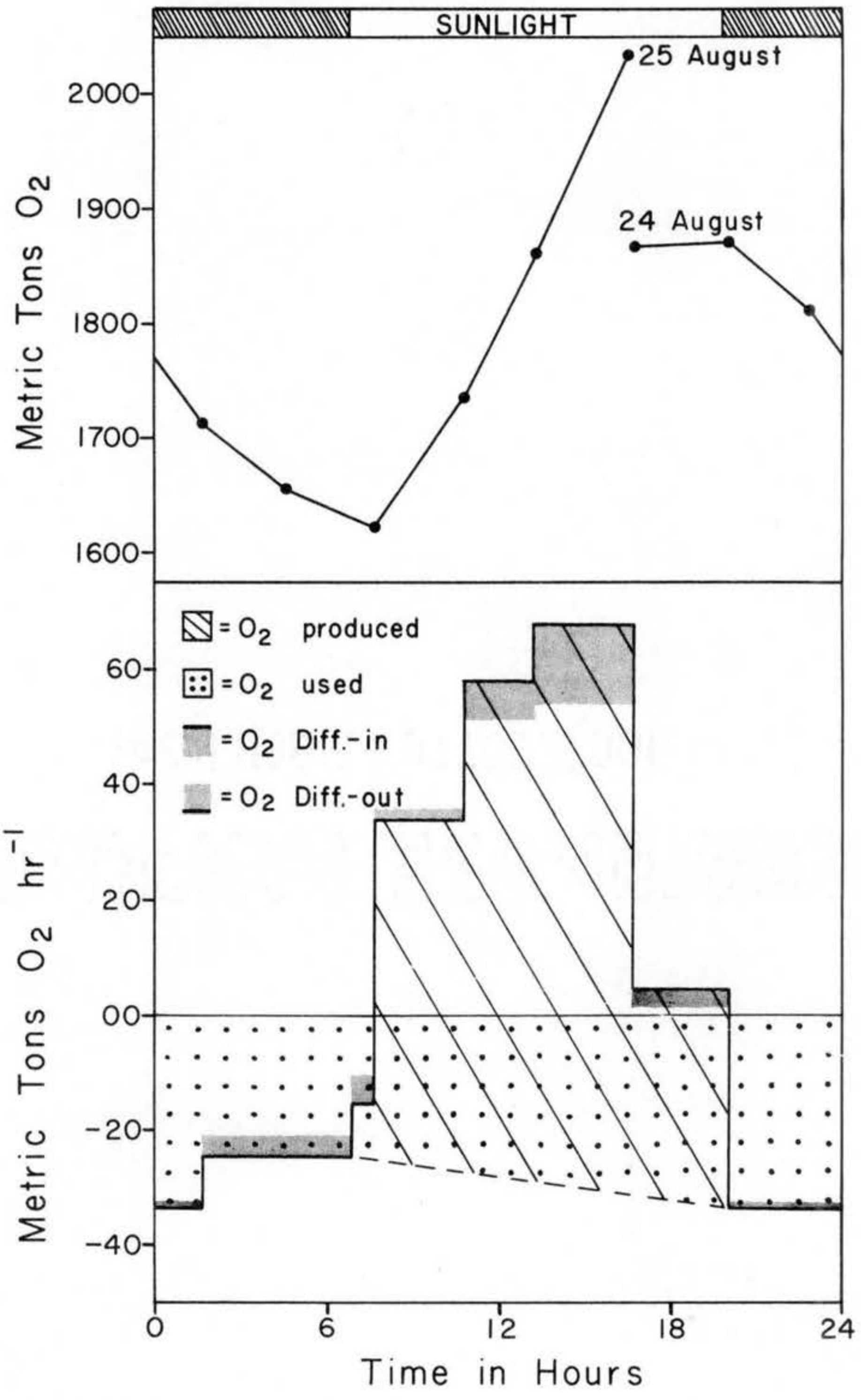

Figure 51. Analysis of oxygen budget of Cimarron arm, 24-25 August 1967, by O_2 curve method. See Table XXXXV for calculations.

estimates of the total oxygen content were volume-weighted, changes in oxygen concentrations in the upper layers of the reservoir had a greater influence on changes in total oxygen content than did changes in lower layers. The contribution of oxygen by inflows was estimated by multiplying the average oxygen concentration at Station I by Cimarron River discharge. Oxygen losses by reservoir discharge were estimated by multiplying oxygen concentrations in the hypolimnion at Station IV by the volume of Cimarron River discharge. This was considered to be a valid approach since total reservoir discharge always exceeded Cimarron River inflow, and Cimarron River inflow traveled along the bottom of the Cimarron arm and was discharged through the dam.

The oxygen budget of the Cimarron arm on 24-25 August 1967 is shown as an example of the method of calculation (Table XLV). To test the validity of the O_2 curve method in estimating the daily oxygen budget, the calculated net gain of 126.9 metric tons O_2 day^{-1} was compared to the observed increase in total oxygen content of the Cimarron arm during the 24-hr period. On 24-25 August 1967, the net gain calculated by the O_2 curve method underestimated the observed net gain in oxygen content by 38.7 metric tons.

The daily oxygen budget was calculated for each of the 11 cloudless sampling dates during 1966-67. Net losses in oxygen content were observed on 1-2 August 1966, 24-25 September 1966, and 28-29 January 1967, and net gains were observed on all other sampling dates. Averaged over 11 cloudless days, daily oxygen gains exceeded calculated daily oxygen losses by 40.9 metric tons O_2 day^{-1} (Table XLVI). The mean calculated net gain underestimated the mean observed gain by 17.4 metric tons O_2 day^{-1}.

TABLE XLV

OXYGEN BUDGET OF CIMARRON ARM, 24-25 AUGUST 1967

(Metric Tons O_2)

Gains		
Production	+ 931.0 day^{-1}	
Diffusion in (k=1.60)	+ 58.9 day^{-1}	
Cimarron R. inflow	+ 1.4 day^{-1}	
	+ 991.3	+ 991.3 day^{-1}
Losses		
Respiration	- 744.1 day^{-1}	
Diffusion out (k=1.60)	- 120.1 day^{-1}	
Reservoir discharge	- 0.2 day^{-1}	
	- 864.4	- 864.4 day^{-1}
	Calculated Net Gain	+ 126.9 day^{-1}
Oxygen Content		
24 August, 16.8 hr	1866.5	
25 August, 16.8 hr	2032.1	
Observed Gain	+ 165.6	+ 165.6 day^{-1}

TABLE XLVI

COMPARISON OF THE AVERAGE CALCULATED DAILY OXYGEN BALANCE AND THE AVERAGE OBSERVED DAILY OXYGEN BALANCE ON 11 CLOUDLESS DAYS TO THE ANNUAL MEAN OBSERVED DAILY OXYGEN BALANCE DURING 1966-67

(Metric Tons O_2)

$\bar{X}$ Gains on Clear Days		
Production	+ 976.1 day^{-1}	
Diffusion in ($\bar{X}$ k=1.49)	+ 42.0 day^{-1}	
Cimarron R. inflow	+ 6.8 day^{-1}	
	+ 1024.9	+ 1024.9 day^{-1}
$\bar{X}$ Losses on Clear Days		
Respiration	- 787.8 day^{-1}	
Diffusion out ($\bar{X}$ k=1.49)	- 194.8 day^{-1}	
Reservoir discharge	- 1.4 day^{-1}	
	- 984.0	- 984.0 day^{-1}
	$\bar{X}$ Calculated Net Gain	+ 40.9 day^{-1}
$\bar{X}$ Oxygen Content on Clear Days		
Beginning 24-hr period	2431.9	
End 24-hr period	2490.2	
$\bar{X}$ Observed Gain	+ 58.3	+ 58.3 day^{-1}
Oxygen Content		
8/1/66, 19.6 hr	1462.1	
8/24/67, 16.8 hr	2032.1	
Observed Net Gain	+ 570.0 in 388 days .	+ 1.5 day^{-1}

Pg and Rt were the dominant factors in determining the oxygen balance of the Cimarron arm on clear days (Table XLVI). Photosynthetic productivity accounted for 95.2% of the total oxygen gains while atmospheric diffusion-in accounted for 4.0% and inflows accounted for 0.8%. Community respiration accounted for 80.0% of the average oxygen loss, while diffusion out of the water accounted for 19.7% and reservoir discharge accounted for 0.3%.

The importance of cloudless days to community metabolism and to the annual oxygen balance is indicated by the large difference in the average observed gain in oxygen content of the Cimarron arm on 11 clear days as compared to the average observed daily gain over a period of 388 days (Table XLVI). The observed gain on clear days was approximately 39 times the annual mean daily gain.

Evaluation of the O_2 Curve Method

Rates of community metabolism obtained by analyses of free-water changes in O_2 or pH-CO_2 are unmistakably higher than estimates obtained by ^{14}C and L & D bottle methods. Many limnologists have been skeptical of the high rates of metabolism obtained by free-water methods. Vinberg (1960) has defended bottle methods, and criticized free-water methods, and concluded that high rates obtained by free-water methods were due to incorrect adjustments for atmospheric reaeration and lack of consideration of gas exchanges with bottom muds. A majority of aquatic ecologists are advocating the adoption of the ^{14}C method as the standard method for determining community metabolism of natural waters. The value of the ^{14}C method as a means of assaying for nutrient deficiencies, for determining relative metabolic rates between depths, or in determining the relative rate of metabolism of oligotrophic waters cannot be denied. However, evidence ~~from this~~ study indicated that bottle methods grossly underestimate metabolic rates in eutrophic waters and are of limited use in studies of community function.

Comparison of the average calculated net gain of oxygen and the average observed net gain of oxygen during clear days indicated that the O_2 curve method is relatively accurate in estimating metabolic rates (Table XLVI). The lower calculated values could have been caused by an underestimation of Pg or an overestimation of Rt, but the difference more likely was caused by errors in estimating the rate of oxygen diffusion through the air-water interface. Assuming that the rate of community metabolism during 1965-66 was approximately the same as the rate of community metabolism during 1966-67, bottle methods underestimated Pg by a factor of 24 and underestimated Rt by a factor of 30 and would be worthless in calculating the oxygen budget of the reservoir.

Greatest sources of error in the O_2 curve method appear to be estimation of the atmospheric reaeration constant and horizontal movements of water masses of different metabolic history through the sampling area during periods of measurement. Errors due to horizontal water movements were eliminated in Keystone Reservoir by averaging observations at several substations within a sampling area. The number of substations required to eliminate errors depended on the heterogeneity of oxygen concentrations within the sampling area and on the velocity of horizontal water movements. In general, the number of substations required increased as surface area and depth increased, with a minimum of three substations required in the downstream reaches.

The metabolism of a reservoir, lake, or pond can be estimated most accurately by determining the average concentration of dissolved oxygen at each meter of depth, multiplying each mean by the volume of water contained in the layer, and using the sum of the products to make an O_2 curve analysis. Depth-weighted analyses give more weight to the euphotic zone, which may be shallow in depth but large in volume. Water bodies which appear to be heterotrophic and apparently are maintained by inflows of organic matter from allocthonous sources actually may be autotrophic. The average Pg/Rt ratio in ~~Keystone~~ Theta Reservoir calculated from unweighted estimates of Pg and Rt (rates per unit area) was 0.98 for 11 clear days during 1966-67. The average Pg/Rt ratio calculated from volume-weighted estimates of Pg and Rt was 1.24. Although autotrophic conditions existed in Keystone Reservoir on clear days, even volume-weighted estimates of Pg/Rt probably would be less than unity if a true annual mean over both clear and cloudy days was obtained.

In the O_2 curve method the length of sampling intervals during a 24-hr period can vary, but samples should be taken at least at 3-hr intervals (Odum and Hoskins 1958). Analyses of O_2 curves obtained in this study indicated that shorter intervals are desirable.

The 3-point method of analysis of O_2 changes has been used by McConnell (1962) in carboy microcosms and by Welch (1968) in Lago Pond, Florida. The method underestimates Pg and Rt if minimum oxygen concentrations do not occur at sunrise and the rate of community respiration is not constant throughout a 24-hr period.

O_2 curves from Keystone Reservoir indicated that the time of minimum and maximum oxygen concentrations in natural waters are not consistent. Variations occur due to changes in cloud cover and the physiological state of the community.) The times of minimum and maximum oxygen concentrations in laboratory microcosms under controlled lighting conditions probably are more predictable. The 3-point method greatly underestimated Pg and Rt as calculated by the 0_2 curve method using data from a shallow pond in India. Using the 3-point method Pg was 26.5 g 0_2 m^{-2} day^{-1} and Rt was 13.2 g 0_2 m^{-2} day^{-1}. An 0_2 curve analysis gave values of 52.11 for Pg and 41.71 for Rt (Appendix). A net diffusion correction of -13.28 g 0_2 m^{-2} day^{-1} was used for both methods. Three-point estimates averaged 91% of Pg and 87% of Rt in eight laboratory microcosms and 71% of Pg and 52% of Rt in Keystone Reservoir when compared to 0_2 curve estimates.

CHAPTER VIII

SUMMARY

1. Physicochemical limnology of Keystone Reservoir during 1965-66 was compared to 1966-67. Spatial and temporal variations in the rate of community metabolism in the Cimarron arm during 1966-67 were estimated by the O_2 curve method. Structural aspects of the plankton community were examined in an effort to explain variations in community function. Phosphorus and oxygen budgets of the Cimarron arm during 1966-67 were estimated by mass-balance calculations. The O_2 curve method was evaluated as a means of estimating community metabolism of reservoirs.

2. All reservoir discharges were made from the epilimnion between August 1965 and July 1966. Between August 1966 and August 1967, water was released from the hypolimnion. The change in discharge level produced marked differences in the intensity of stratification, circulation patterns, and effects of impoundment on water quality.

3. During 1965-66, highly mineralized Cimarron River water which formed an underflow along the bottom of the Cimarron arm built up in volume behind the dam and flowed up the Arkansas arm, undercutting lighter water of Arkansas River origin. Salt-heavy water formed partial meromixis below 12 m of depth. Underflows of cool, aerated Cimarron River water into the monimolimnion produced mesothermy and a negative heterograde oxygen distribution during the winter. During the

summer, stable thermal stratification imposed upon chemical stratification resulted in a thermocline at 5 m of depth and an extreme clinograde oxygen distribution with anoxia below 8 m.

4. During 1966-67, the Cimarron River underflow was discharged through sluice gates and no build-up of salt-heavy water occurred. Seasonal thermal stratification was similar to that of warm monomictic lakes. A fall overturn occurred between September and October 1966. Except for a density current in the Cimarron arm, complete mixing occurred during the winter of 1966-67. Heating of surface waters during May 1967 re-established thermal stratification.

5. During 1966-67, water from the Arkansas River formed an overflow down the Arkansas arm and up the Cimarron arm for approximately 30 km above the dam before turning and flowing back through the Cimarron arm as a downstream interflow. The underflow of Cimarron water combined with the interflow of Arkansas water to produce a downstream mass flow through the lower half of the Cimarron arm greater than the volume of water being discharged through the dam. The excess volume, primarily of Arkansas River origin but containing some water of Cimarron origin, formed an underflow up the Arkansas arm for a distance of at least 20 km above the dam.

6. The minimum retention time of the downstream underflow of Cimarron River water was estimated to be 6 days. The Arkansas River water which traveled as an overflow down the Arkansas arm and up the Cimarron arm and then traveled back down the Cimarron arm as an interflow to the dam was retained a minimum of 18 days. Water from this interflow which was not released from the dam and which traveled back up the Arkansas arm as an underflow and then traveled back down the

Arkansas arm and up the Cimarron arm as an interflow and then traveled back down the Cimarron arm to the dam was retained in the reservoir at least 48 days.

7. Water quality in Keystone Reservoir was better in all respects during 1966-67 than during 1965-66. Conductivity and turbidity were significantly lower in 1966-67 than in 1965-66, while dissolved oxygen and bicarbonate concentrations were higher.

8. Temperature, conductivity, turbidity, dissolved oxygen, carbonates, and pH decreased as water flowed through the reservoir, while bicarbonates and carbon dioxide increased. Although the change in reservoir discharge level between 1965-66 and 1966-67 produced an improvement in the quality of water in Keystone Reservoir, the change was detrimental to the quality of reservoir discharge. The change from epilimnetic discharge to hypolimnetic discharge decreased the effectiveness of the reservoir in reducing conductivity from 78% to 48% and in reducing turbidity from 92% to 74% and resulted in an increase in the reduction of dissolved oxygen concentration from 10% to 68%.

9. Surface and subsurface currents measured by the free-drag method had an average velocity of 3.02 ± 0.44 m min^{-1}. Greatest velocities were attained in surface waters when wind driven currents were in the direction of mass flow. High velocities also were measured in the Cimarron underflow. Slower currents were observed at mid-depths near the shearing plane between opposing mass flows and in the upstream underflow in the Arkansas arm. Speed and direction of surface currents as measured by the free-drag method were similar to estimates made using dye plumes. No conclusive evidence of Coriolis effect was observed. Both clockwise and counter-clockwise currents were observed,

with the direction of curvature being determined by proximity to shore, wind direction, and direction of mass flow.

10. Concentrations (g m^{-3}) of dissolved and suspended solids generally decreased downstream, while amounts (g m^{-2}) increased. Concentrations of dissolved solids increased with depth. Concentrations of suspended solids were highest in the Cimarron underflow and were relatively uniform at other depths.

11. Concentrations (g m^{-3}) of chloride ion on the average were equivalent to 32% of the concentration of total dissolved solids and were equivalent to 24% of the μmhos of specific conductance. Concentrations (g m^{-3}) of total dissolved solids on the average were equivalent to 75% of the μmhos of specific conductance. Turbidity units on the average were equivalent to 96% of the concentration (g m^{-3}) of suspended solids.

12. Sediment load of the Cimarron River was not directly proportional to run-off but increased more rapidly with increasing discharge. Total inflow of suspended solids into the Cimarron arm during 1965-66 was 9.1 times the total inflow during 1966-67, while the annual Cimarron River discharge during 1965-66 was only 1.3 times the annual discharge of 1966-67. Approximately 86% of the average annual inflow of suspended solids from the Cimarron River (212.9×10^3 metric tons) was lost to sediments. Assuming that the rate of sedimentation during 1965-67 is a valid estimate of the long-term rate of sedimentation, the Cimarron arm of Keystone Reservoir would have a life expectancy of about 20 centuries before sediments fill the reservoir to normal power pool level.

13. The heat content of Keystone Reservoir varied from a maximum of 21,289 cal cm^{-2} in August 1965 to a minimum of 3,451 cal cm^{-2} in January 1967. The average annual heat budget of Keystone Reservoir was 17,217 cal cm^{-2}, and the reservoir had an average negative winter heat income of -995 cal cm^{-2}. Keystone Reservoir would be classified thermally as a second-class lake according to the scheme of classification of Birge (1915). Heat gains from differences in the heat content of inflows and outflows were not as important to the annual heat budget as solar radiation. Heat gained by inflows, averaged over all heating and cooling periods during 1965-67, was 306 cal cm^{-2}, and heat lost to outflows was 270 cal cm^{-2}, yielding an average net gain of only 36 cal cm^{-2}. Evaporation heat losses probably were the major source of heat loss from Keystone Reservoir.

14. Concentrations of total phosphorus in the Cimarron arm ranged from a minimum of 10 mg P m^{-3} at Station III in January 1967 to a maximum of 994 mg P m^{-3} at Station I in August 1967. High concentrations of dissolved forms of phosphorus usually were associated with low concentrations of particulate phosphorus (PP), and high concentrations of particulate phosphorus usually were associated with low concentrations of dissolved phosphorus. Dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) occasionally were absent or below the minimum detectable concentration in surface waters. PP was present in all samples collected during 1966-67.

In general, concentrations (mg m^{-3}) of total phosphorus increased with depth and decreased downstream, while amounts (mg m^{-2}) increased downstream. The annual mean concentration of DIP at Station IV was 48.8% higher than the annual mean concentration of DIP in the rest of the Cimarron arm, excluding Cimarron River data. This increase in DIP at Station IV supports the hypothesis that water in the lower end of the Cimarron arm during 1966-67 was primarily of Arkansas River origin, since phosphate concentrations in the Arkansas arm averaged 48% higher than phosphate concentrations in the Cimarron arm in 91 observations made by the U. S. Geological Survey during 1965-66.

Concentrations of phosphorus were greatest in the density current flowing along the bottom of the Cimarron arm. Reductions in PP between Stations I and II of 48% and between Stations II and III of 57% closely paralleled reductions in suspended solids between Stations I and II of 46% and between Stations II and III of 58%. This relationship suggests that high concentrations of phosphorus at Station I probably were due to phosphorus associated with silt and clays suspended in Cimarron River inflows.

15. In general, total phosphorus content increased throughout 1966-67, with most significant increases occurring during high inflows of the Cimarron River in June and July. Temporal variations in total phosphorus content closely followed variations in content of PP, which was the most abundant form of phosphorus during most of the year.

The gain in total phosphorus content of the Cimarron arm from 14.3 to 45.8 metric tons between September 1966 and August 1967 represents an increase of 320%. This rate of increase is larger than any other known from the literature and is 12.8 times the rate of increase of phosphorus in Lake Erie during the past 20 years. Of the 108.3 metric tons of total phosphorus contributed by the Cimarron River, 38.3% was retained in the reservoir. Approximately 74% of the amount retained appeared as an increase in phosphorus content of the water, and the remaining 26% apparently was lost to sediments by chemical precipitation and sedimentation of particulate matter. Of the 17.0 metric tons of PP retained in the reservoir, 1.5 metric tons of PP were converted to other forms of phosphorus by biological activity. Approximately 0.8 metric tons were converted to DIP, and 0.7 metric tons were converted to DOP. These calculations based on only a 12-month observation period may either underestimate or overestimate the actual long-term rate of eutrophication of Keystone Reservoir.

16. A computer program was developed to compute rates of community metabolism from O_2 changes occurring during a 24-hr period. The program performed a valid O_2 curve analysis of approximately 90% of the data tested. Average coefficients of variation for the method in Keystone Reservoir ranged from 2.7% at Station I to 9.4% at Station IV for gross productivity (Pg) and 1.7% at Station I to 11.7% at Station IV for total community respiration (Rt).

17. Slopes of least squares regression lines fitted through observed "daytime" negative rates of O_2 change in laboratory microcosms were significantly less ($\alpha = 0.05$) than zero, suggesting an increase in the rate of respiration during the day. Slopes of regression lines were not significantly different ($\alpha = 0.05$) from slopes of hypothetical daytime respiration lines drawn between pre-sunrise and post-sunset negative rates-of-change.

18. The average rate of Pg as estimated by the O_2 curve method was equivalent to 0.69 of the pH-CO_2 curve estimate and 1.95 of the Light & Dark bottle estimate in eight laboratory microcosms containing water from Keystone Reservoir. Rt estimated by the O_2 method averaged 0.54 of the pH-CO_2 estimate and 2.35 of the L & D bottle estimate.

A similar pattern of variation in Pg and Rt among microcosms was obtained with pH-CO_2 and O_2 curve methods. No significant differences ($\alpha = 0.05$) in Pg and Rt were detected among microcosms by L & D bottles, which apparently inhibited metabolic rates.

19. During 1966-67, 176 oxygen curves were obtained from the Cimarron arm of Keystone Reservoir. Mean Pg ranged from 11.34 g O_2 m^{-2} day^{-1} at Station I to 38.63 at Station IV, and mean Rt ranged from 11.04 g O_2 m^{-2} day^{-1} at Station I to 54.12 at Station IV. Pg/Rt ratios indicated that on the average autotrophic conditions existed at Stations I and II, and heterotrophic conditions existed at Stations III and IV.

Depth-weighted annual means of community metabolism showed a different spatial variation than area-based estimates, with the average rate of Pg per m^3 of euphotic zone (EZ) highest at Station I and lowest at Station II. The spatial variation of average Rt m^{-3} was similar to that of Pg with a maximum at Station I and a minimum at Station II.

20. Pg and Rt as measured by the O_2 curve method during 1966-67 greatly exceeded Pg and Rt measured by the L & D bottle method during 1965-66. Estimates of Pg by the O_2 curve method during 1966-67 also greatly exceeded estimates of Pg during 1966-67 made by Spangler (1969) using the chlorophyll-light intensity method of Ryther and Yentsch (1957).

21. Temporal variations in Pg and Rt were large. Patterns of variation at Stations I and II were distinct, while patterns of variation at Stations III and IV were similar. Pg varied from a minimum of 2.09 g O_2 m^{-2} day^{-1} at Station I in January 1967 to a maximum of 129.77 g O_2 m^{-2} day^{-1} at Station IV in November 1966. Rt varied from a

minimum of 1.12 g O_2 m^{-2} day^{-1} at Station I in January 1967 to a maximum of 171.20 g O_2 m^{-2} day^{-1} at Station IV in November 1966.

22. High metabolic rates which occurred at relatively low light intensities during the fall and winter at Stations III and IV may have been caused by unidentified small green cells, which were by far the most abundant form in surface waters.

23. A relationship between the magnitude of Pg and Rt and the trophic state of the plankton community apparently existed. When Pg and Rt were high, Pg/Rt ratios were low. When Pg and Rt were low, Pg/Rt ratios were high.

24. Rates of community metabolism in Keystone Reservoir during 1966-67 were within the range of rates estimated by O_2 and pH-CO_2 curve methods for other waters. Metabolic rates in Keystone exceeded the maximum rates obtained by ^{14}C and L & D bottle methods in other waters. When a consideration of water depth is made, the highest rates of community metabolism were obtained by O_2 curve analysis of oxygen data of George (1961) for a shallow pond in Delhi, India (Pg = 52.1 g O_2 m^{-2} day^{-1} and Rt = 41.7 g O_2 m^{-2} day^{-1}).

25. Solar radiation on clear days when estimates of community metabolism were made always exceeded monthly averages. Solar radiation ranged from a minimum of 253 g cal cm^{-2} day^{-1} in December 1966 to a maximum of 658 g cal cm^{-2} day^{-1} in July 1967. No apparent relationship existed between rates of Pg and Rt and solar radiation. Solar radiation apparently did not limit photosynthesis and no evidence of photoinhibition due to high light intensities was found.

26. Annual means of efficiency of Pg were 1.97% for Station I, 3.87% for Station II, 6.35% for Station III, and 8.23% for Station IV.

Efficiencies of Pg found in Keystone Reservoir were in the upper range of those reported in the literature. Variations in Pg, solar radiation, and efficiency during eight consecutive days at Station III in August 1967 indicated an inverse relationship between efficiency and solar radiation and a direct relationship between efficiency and Pg.

27. Direct relationships between Pg and chlorophyll a and between Rt and biomass existed between Stations I and II, but inverse relationships existed among Stations II, III, and IV. Concentrations of chlorophyll a in the EZ decreased between Stations II, III, and IV, while Pg (g O_2 m^{-3} of EZ day^{-1}) increased. Average biomass concentrations in the water column decreased between Stations II, III, and IV while Rt (g O_2 m^{-3} day^{-1}) increased. A relation between average organism size and rate of community metabolism was suggested by relatively high values of Rt occurring at relatively low concentrations of biomass at Stations III and IV during September and November 1966 and January 1967 when species diversity was extremely low and small unidentified μ-cells were abundant.

28. Diatoms were by far the most abundant phytoplankter and probably made a significantly greater contribution to biomass than did bacteria at Station I. Greater seasonal changes in plankton occurred at Stations II, III, and IV than at Station I. In general, solitary Chlorophyta were the most abundant form of phytoplankton, with diatoms and bluegreens in lesser abundance. Bluegreens were most abundant during late summer and fall. Diatoms were most abundant at Stations II, III, and IV in the spring. A large bloom in desmids was observed at all stations during May and early June 1967. Green μ-cells were common to abundant in the surface waters of Station IV during most of

1966-67. The greater influence of small organisms with high metabolic rates at the deeper stations was shown by increases in annual mean Rt/biomass ratios from 0.25 at Station I to 0.69 at Station IV.

29. Pn/biomass ratios decreased from 1.18 at Station I to 0.97 at Station IV, and ratios at all stations were characteristic of the first stage of succession proposed by Margalef (1958). Immaturity of the reservoir ecosystem was also suggested by large temporal variations in community structure and function and by high rates of community metabolism.

30. Patchiness of the plankton population increased downstream and decreased with depth. Average variation in Pg and Rt among substations within a sampling area was lowest at Station I (s^2 of Pg = 0.10, s^2 of Rt = 0.04) and highest at Station IV (s^2 of Pg = 21.10, s^2 of Rt = 39.88). Analyses of variation of biomass among substations within depths gave coefficients of variation of 32% at 1 m, 19% at 8 m, and 2% at 14 m. The high coefficients of variation for samples at 1 and 8 m of depth were indicative of the patchiness of the phytoplankton population in the epilimnion. The low coefficient of variation at 14 m of depth indicated a lack of patchiness of seston in the hypolimnion. In future studies the number of substations within a sampling area should be increased downstream as the reservoir becomes wider to provide a better estimate of the true population mean.

31. Annual mean concentrations of 5-day BOD decreased from 3.8 g O_2 m^{-3} at Station I to 1.1 g O_2 m^{-3} at Station IV, 20-day BOD decreased from 11.2 g O_2 m^{-3} to 4.5 g O_2 m^{-3}, and COD decreased from 176 g O_2 m^{-3} to 18 g O_2 m^{-3}. The BOD reaction constant k, which is an indication of the biodegradability of organic matter, decreased between Stations I

and IV. No significant differences in average concentrations of BOD and COD or in BOD k values were found among depths within stations. Highest concentrations of BOD and COD were present in cold months, and lowest concentrations were present in warm months. BOD k values generally were higher in winter than in summer. BOD concentrations in Keystone Reservoir were within the range of concentrations reported for other reservoirs. COD concentrations in Keystone Reservoir generally were higher than values reported for other reservoirs.

32. Total oxygen content of the Cimarron arm exceeded potential oxygen demand on all sampling dates. However, since estimates of oxygen content were made only on clear days, they must be considered as maximum values, and on some cloudy days potential oxygen demand may have exceeded total oxygen content. The relationship between oxygen content and potential oxygen demand was most favorable during November and December 1966 when the reservoir would have had more than 6.5 g O_2 m^{-3} if the potential oxygen demand had been exerted. During June, July, and August 1967, exertion of the potential oxygen demand would have reduced average oxygen concentrations below 4 g O_2 m^{-3}.

33. The daily oxygen budget was calculated for each of the 11 cloudless sampling dates during 1966-67. Daily oxygen gains exceeded calculated daily oxygen losses by 40.9 metric tons O_2 day^{-1}. The mean calculated net gain underestimated the mean observed gain by 17.4 metric tons O_2 day^{-1}. Pg and Rt were the dominant factors in determining the oxygen balance of the Cimarron arm on clear days. Photosynthetic productivity accounted for 95.2% of the total oxygen gains, while atmospheric diffusion-in accounted for 4.0% and inflows accounted for 0.8%. Community respiration accounted for 80.0% of the average

oxygen loss, while diffusion out of the water accounted for 19.7% and reservoir discharge accounted for 0.3%. The observed gain on clear days was approximately 39 times the annual mean daily gain. This relationship indicates the importance of clear days to the annual oxygen budget.

34. Greatest sources of error in the O_2 curve method appear to be estimation of the atmospheric reaeration constant and horizontal movements of water masses of different metabolic history through the sampling area during periods of measurement. Errors due to horizontal water movements were eliminated in the present study by averaging observations at several substations within a sampling area. The number of substations required to eliminate errors depended on the heterogeneity of oxygen concentrations within the sampling area and on the velocity of horizontal water movements. In general, the number of substations required increased as surface area and depth increased, with a minimum of three substations required in the downstream reaches.

35. The metabolism of a reservoir can be estimated most accurately by determining the average concentration of dissolved oxygen at each meter of depth, multiplying each mean by the volume of water contained in the layer, and using the sum of the products to make an O_2 curve analysis. Depth-weighted analyses give more weight to the euphotic zone, which may be shallow in depth but large in volume. The average Pg/Rt ratio in Keystone Reservoir calculated from unweighted estimates of Pg and Rt (rates per unit area) was 0.98 for 11 clear days during 1966-67. The average Pg/Rt ratio calculated from volume-weighted estimates of Pg and Rt was 1.24.

36. The 3-point method of analysis of O_2 changes used by McConnell (1962) in carboy microcosms and by Welch (1968) in Lago Pond, Florida, probably underestimates Pg and Rt. O_2 curves from Keystone Reservoir indicated that the time of minimum and maximum oxygen concentrations in natural waters are not consistent. The times of minimum and maximum oxygen concentrations in laboratory microcosms under controlled lighting conditions probably are more predictable. Three-point estimates averaged 91% of Pg and 87% of Rt in eight laboratory microcosms and 71% of Pg and 52% of Rt in Keystone Reservoir when compared to O_2 curve estimates.

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APPENDIX

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C     *****   DIURNAL   OXYGEN   CURVE   PROGRAM    *****
C     DEVELOPED BY REX L. ELEY, RESERVOIR RESEARCH CENTER, OKLAHOMA STATE UNIV,
C         AND MAX M. MCKEE, OKLA STATE UNIV COMPUTER CENTER.
C     THIS PROGRAM READS IN DISSOLVED OXYGEN CONCENTRATION AND PERCENT OXYGEN
C         SATURATION OF THE SURFACE WATER AND DISSOLVED OXYGEN CONTENT OF THE
C         WATER COLUMN(G O2/M**2) OR WATER MASS(G O2) AND CALCULATES PRIMARY
C         PRODUCTIVITY, COMMUNITY RESPIRATION, AND ATMOSPHERIC DIFFUSION, AND
C         OPTIONALLY PLOTS THE DIURNAL OXYGEN RATE-OF-CHANGE CURVE.
C     A DIURNAL DATA SET SHOULD CONSIST OF AT LEAST 9 OBSERVATIONS
C          (3 HOUR INTERVALS) TAKEN DURING A 24-HR PERIOD, PREFERABLY WITH
C          OBSERVATIONS AT SUNRISE AND SUNSET AND WITH THE FIRST AND LAST
C          OBSERVATIONS MADE AT THE SAME TIME OF DAY.  MORE FREQUENT
C          OBSERVATIONS ARE DESIRABLE, AND THE PROGRAM IS DIMENSIONED TO ACCEPT
C          UP TO 99 OBSERVATIONS DURING A 24-HR PERIOD.
C     OBSERVATIONS MUST BE MADE ON THE SAME WATER MASS OR  ON WATER MASSES OF
C         SIMILAR METABOLIC HISTORY THROUGHOUT THE 24-HR PERIOD.  IF THIS
C         RESTRICTION IS MET, ALL CHANGES IN THE DISSOLVED OXYGEN CONTENT OF
C         THE WATER MASS ARE DUE TO THE NET EFFECT OF PHOTOSYNTHESIS,
C         RESPIRATION, AND DIFFUSION OF OXYGEN ACROSS THE AIR-WATER INTERFACE.
C     BY DETERMINING THE TOTAL DISSOLVED OXYGEN CONTENT OF THE WATER COLUMN
C         (G O2/M**2) AT EACH OBSERVATION TIME, ERRORS DUE TO VERTICAL OXYGEN
C         TRANSPORT BY CONVECTION CURRENTS AND EDDY DIFFUSION ARE ELIMINATED.
C     CALCULATIONS ARE ACCOMPLISHED IN SUBROUTINES: CALCK, SHUFLE, RESP, AREA,
C         PLT, AND PNCH.
C     THIS PROGRAM WAS PUNCHED ON AN IBM 029 KEYPUNCH USING EBCDIC CODE.  THE
C         PROGRAM IS COMPATABLE WITH THE IBM 360 FORTRAN(F) COMPILER.
      COMMON T,QK,DELT,INDX,MARK,IERROR
      COMMON /CAL/  SURFR,DEF
      COMMON/HEAD/ST1,SUB1,MO1,DY1,YR1
      DIMENSION   TYPE(6,3),TITLE(20),FMT(20)
      DATA TYPE/'CALC','ULAT','ED B','Y AV','ERAG','ING ',
     *      'SUPP','LIED',' FOR',' ENT','IRE ','SET ',
     *      'SUPP','LIED',' FOR',' THI','S DA','TE '     /
      DIMENSION   SUN(12,31),  SET(12,31),RATE (12,31)
      DIMENSION T(100),SURF(100),SAT(100),SUM(100),QK(100),DIFF(100),
     * DELT(100),SURFR(100),SUMR(100),DEF(100)
      INTEGER ST,SUB,YR,DY,ST1,SUB1,YR1,DY1
    1 FORMAT(20A4)
    2 FORMAT(1H   ,10X,3F10.2)
    3 FORMAT(1H ,5X,F10.2,15X,F10.2,15X,F10.1,15X,F10.1,/,
     *     1H ,15X,F10.2,15X,F10.2,15X,F10.2,15X,F10.2,F10.2,F10.3)
    4 FORMAT(6X,2H14,2I2,3I3,4X,2I10,4I5    )
    5 FORMAT( 1H ,40X,8HSTATION ,I2,5X,11HSUBSTATION ,I2,5X,5HDATE ,I2,1
     *H/,I2,1H/,I2  ,//)
    6 FORMAT(  1H1 )
    7 FORMAT(1H0,9X,'GROSS PROD = ',F10.2,2X,'G UF O2/M**2/24HR',10X,
     *   'DIFFUSION-OUT = ',F7.2,2X,'G OF O2/M**2/24HR',  /,
     *   1H ,9X,'TOTAL RESP = ',F10.2,2X,'G OF O2/M**2/24HR',10X,
     * 'DIFFUSION-IN  = ',F7.2 ,2X,'G UF O2/M**2/24HR',/,
     * 1H ,9X'NET PROD    = ',F10.2,2X,'G OF O2/M**2/24HR',/,
     *  1H ,9X,'PROD/RESP  = ',  F10.2,29X,'DIFFUSION CONSTANT (K)  = ',
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     *  F6.2,2X,6A4,//   )
    8 FORMAT(  1H0 ,11X,'TIME     INTERVAL'8X,'SURFACE       SAT'9X,
     *  'SURFACE     SURF RT',8X,'COLUMN     COL RT      DIFF   CORR RATE',/
     *  /,1H ,12X'HR',8X,'HR',13X,'SAT',7X,'DEF',10X,'G/M**3    G/M**3/HR
     *',      7X,'G/M**2  G/M**2/HR     CORR    G/M**2/HR   '       )
    9 FORMAT(1H ,5X,F10.2,10X, F10.2, 2F10.1)
   10 FORMAT( 3I5,F5.2,F5.2)
   11 FORMAT(2I5,3F10.2)
   12 FORMAT(1H0,  10X,'VALUES ADJUSTED ACCORDING TO CLASS(',I1,1H, ,I1,  1H)
     *  1H),/,1H ,10X,'RESPIRATION LINE BEGINS AT ', F8.2,' HOURS  AND ENDS
     *NDS  AT  ',F8.2,'HOURS'    )
   13 FORMAT(1H0,17X,'TIME  INTERVAL', 6X,'RATE',/   )
   14 FORMAT(1H1,  20X,20A4    )
   15 FORMAT(  1H1,50X,'DEFINITION  OF  CLASSES  OF  DATA',/,67X,'FOR',/
     *  30X,'PLACEMENT  OF  ENDPOINTS  OF  THE  HYPOTHETICAL  DAYLIGHT
     *RESPIRATION  LINE',///,10X,'MORNING CLASSES',/,20X,'CLASS(1,X)...I
     *F  MINIMUM MORNING INTERVAL IS BETWEEN INTERVAL NEAREST SUNRISE AN
     *D NOON,',/,32X,
     *    ' RESPIRATION LINE WILL BE DRAWN FROM THE LEADING EDGE OF THE
     * MINIMUM INTERVAL')
   16 FORMAT(20X,'CLASS(2,X)...IF THE MINIMUM INTERVAL OCCURS BEFORE THE
     * INTERVAL NEAREST SUNRISE AND IF LESS THAN 25 PERCENT OF',/,33X,'T
     *HE INTERVAL CONTAINING SUNRISE IS LIGHT AND THE SR INTERVAL IS NEG
     *ATIVE, THE LINE WILL BE DRAWN',/,33X,'FROM THE RIGHT EDGE OF THE S
     *R INTERVAL.')
   17 FORMAT(20X,'CLASS(3,X)...IF MORE THAN 25 PERCENT OF THE SR INTERVA
     *L IS LIGHT OR IF THE SR INTERVAL IS POSITIVE, THE RATE OF',/,33X,'
     *THE FIRST PRECEDING NEGATIVE INTERVAL WILL BE EXTENDED TO SR AND T
     *HE LINE WILL BE DRAWN FROM THAT',/,33X,'POINT.')
   18 FORMAT(10X,'EVENING POINT',/,20X,'CLASS(X,1)...IF THE EVENING MINI
     *MUM INTERVAL OCCURS BETWEEN NOON AND THE INTERVAL NEAREST SUNSET,
     *THE LINE WILL',/,33X,'BE DRAWN TO THE LEFT EDGE OF THE MINIMUM INT
     *ERVAL.')
   19 FORMAT(20X,'CLASS(X,2)...IF THE MINIMUM INTERVAL OCCURS AFTER THE
     *INTERVAL NEAREST SS, THE RATE OF THE MINIMUM INTERVAL WILL',/,33X,
     *'BE EXTENDED BACK TO THE RIGHT EDGE OF THE INTERVAL CONTAINING SS
     *AND THE LINE WILL BE DRAWN TO THAT',/,33X,'POINT.')
      WRITE(6,15)
      WRITE(6,16)
      WRITE(6,17)
      WRITE(6,18)
      WRITE(6,19)
C     DEFINITION OF INPUT ARGUMENTS
C      A. INPUT ARGUMENTS SPECIFIED ON CARD 1 OF DATA SET
C          NTIMES...TOTAL NUMBER OF DIURNALS IN DATA SET OR NUMBER OF
C                   SUNRISE(SR)-SUNSET(SS) CARDS TO BE READ.
C          NPLT.....EQUALS 0 OR BLANK FOR NO PLOTTED RATE-OF-CHANGE CURVE,
C                   EQUALS 1 FOR PLOTTED RATE-OF-CHANGE CURVE.
C          NPUNCH...EQUALS 0 OR BLANK FOR NO PUNCHED OUTPUT,
C                   EQUALS 1 FOR PUNCHED OUTPUT.
C          BOUND....UPPER LIMIT OF ABSOLUTE VALUE OF ATMOSPHERIC DIFFUSION
C                   CONSTANT(K) WHICH IS CALCULATED BETWEEN EACH PAIR OF
C                   NIGHTTIME SURFACE RATES-OF-CHANGE.  IF THE CALCULATED K
C                   EXCEEDS BOUND, BOUND IS USED AS K FOR THE TIME INTERVAL IN
C                   COMPUTING THE AVERAGE NIGHTTIME DIFFUSION CONSTANT.
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C          SETVAL...OPTIONAL DIFFUSION CONSTANT...IF GIVEN, THIS CONSTANT WILL
C                   BE USED FOR THE ENTIRE DATA SET AND WILL OVERRIDE DAILY
C                   DIFFUSION CONSTANTS SUPPLIED AS RATE(MO,DY) ON SUNRISE-
C                   SUNSET CARDS AND WILL OVERRIDE DIFFUSION CONSTANTS
C                   CALCULATED FROM NIGHTTIME OXYGEN RATES-OF-CHANGE IN
C                   SUBROUTINE CALCK.
11110 READ(5,10) NTIMES, NPLT ,NPUNCH,BOUND,SETVAL
C      B. INPUT ARGUMENTS SPECIFIED ON SUNRISE-SUNSET CARDS
C          SUN(MO,DY)...SUNRISE TIME IN HOURS (0.00-24.00) FOR MONTH MO AND DAY
C                   DY.
C          SET(MO,DY)...SUNSET TIME IN HOURS FOR MONTH MO AND DAY DY.
C          RATE(MO,DY)..OPTIONAL DIFFUSION CONSTANT SUPPLIED FOR MONTH MO AND
C                   DAY DY...NORMALLY USED IF THE RATE OF ATMOSPHERIC DIFFUSION
C                   WAS ESTIMATED INDEPENDENTLY ON EACH OBSERVATION DATE BY THE
C                   PLASTIC DOME METHOD (COPELAND AND DUFFER, L&O, 1964).
C                   FOR DAILY CONSTANTS TO BE USED, SETVAL MUST BE OMITTED.  IF
C                   BOTH SETVAL AND RATE(MO,DY) ARE OMITTED, A DAILY ATMOSPHERIC
C                   DIFFUSION CONSTANT WILL BE CALCULATED BY SUBROUTINE CALCK.
      READ(5,11)( MO,DY,SUN(MO,DY),SET(MO,DY),RATE (MO,DY)
     * ,KOUNT=1,NTIMES)
C     DEFINITION OF INPUT DATA ITEMS
C      A. INPUT DATA ITEM SPECIFIED ON FIRST CARD AFTER SR-SS CARDS
C          TITLE...THE NAME OF THE WATER BODY OR STREAM BEING STUDIED.  THIS
C          IDENTIFICATION WILL BE PRINTED ON OUTPUT PAGES ABOVE EACH DIURNAL
C          BUT WILL NOT BE PUNCHED ON OUTPUT CARDS CONTAINING METABOLIC VALUES.
      READ(5,1)  TITLE
      READ(5,1)  FMT
         READ(5,FMT)ST,SUB,YR,MO,DY,T1,SAT1,SURF1,SUM1
11111 CONTINUE
      ST1 = ST
      SUB1 = SUB
      YR1 = YR
      MO1 = MO
      DY1 = DY
      WRITE(6,14)  TITLE
      WRITE(6,5) ST1,SUB1,MO1,DY1,YR1
      T(1) = T1
      SURF(1) = SURF1
      SAT(1) = SAT1
      SUM(1) = SUM1
      SR = SUN(MO1,DY1)
      SS = SET(MO1,DY1)
      RATES=RATE(MO1,DY1)
      DO 111 I = 2,100
C      B. INPUT DATA ITEMS TO BE GIVEN ON ALL OTHER DIURNAL DATA CARDS
C     THIS PROGRAM IS WRITTEN TO READ INPUT DATA CARDS FROM VARIABLE FORMATS.
C         A CARD DEFINING THE FORMAT OF THE 9 INPUT DATA ITEMS, WHICH ARE
C         DEFINED BY THE FOLLOWING COMMENT CARDS, SHOULD BE PUNCHED AND PLACED
C         AFTER TITLE CARD.  AN INPUT DATA CARD CONTAINING THE 9 INPUT DATA
C         ITEMS SHOULD BE PUNCHED FOR EACH OBSERVATION TIME OF EACH DIURNAL.
C     AFTER SOURCE DECK AND CONTROL CARDS, INPUT DATA CARDS SHOULD BE ARRANGED
C          IN THE FOLLOWING ORDER: INPUT ARGUMENT CARD, SUNRISE-SUNSET CARDS FOR
C          ALL DIURNALS, TITLE CARD NAMING WATER BODY, VARIABLE FORMAT CARD ,
C          AND INPUT DIURNAL DATA CARDS WITH THE CARDS FOR EACH DATE AND
C          LOCATION GROUPED TOGETHER IN THE SEQUENCE IN WHICH THE DATA WERE
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C          TAKEN.
C          ST...STATION NUMBER OR LOCATION IDENTIFICATION
C          SUB..SUBSTATION NUMBER OR REPLICATE IDENTIFICATION
C          YR...YEAR
C          MO...MONTH
C          DY...DAY...NOTE...A DIURNAL USUALLY ENCOMPASES TWO DATES (UNLESS
C                   OBSERVATIONS ARE BEGUN AT 0.00 HOURS) BUT DY IS ALWAYS
C                   GIVEN AS THE DATE IN WHICH THE LIGHT PERIOD OCCURRED.
C          T....TIME IN HOURS(0.00-24.00) OF OBSERVATION.
C          SAT..PERCENT OXYGEN SATURATION OF SURFACE WATER AT TIME T.
C          SURF.DISSOLVED OXYGEN CONCENTRATION(G/M**3) OF SURFACE WATER AT
C                   TIME T.
C          SUM..AMOUNT OF DISSOLVED OXYGEN IN THE WATER COLUMN(G O2/M**2) OR IN
C                   THE WATER MASS(G O2) AT TIME T.
         READ(5,FMT)ST,SUB,YR,MO,DY,T(I),SAT(I),SURF(I),SUM(I)
         IF( ST.NE.ST1 .OR. SUB.NE.SUB1 ) GO TO 222
         IF( YR.NE.YR1 .OR. MO.NE.MO1 .OR. DY.NE.DY1 ) GO TO 222
  111 CONTINUE
      CALL ERROR( 1 )
      GO TO 8888
  222 INDX = I-2
      T1 = T(I)
      SURF1 = SURF(I)
       SAT1 = SAT(I)
      SUM1 = SUM(I)
      DO 444  I = 1,INDX
         DELT(I) = T(I+1) - T(I)
         IF( DELT(I).GE.0.0 ) GO TO 333
         MARK = I+1
         DELT(I) = 24.0 + DELT(I)
  333    SURFR(I) = (SURF(I+1) - SURF(I))/DELT(I)
         SUMR(I) = (SUM(I+1) - SUM(I))/DELT(I)
         DEF(I) = 1.0 - (SAT(I) + SAT(I+1))/2.0
  444 CONTINUE
      CALL CALCK(SR,SS,RATES,SETVAL,BOUND,QAVR,KT)
      DO 6666 I = 1,INDX
         DIFF(I) = DEF(I)*QAVR
         QK(I) = SUMR(I)+DIFF(I)
 6666 CONTINUE
      DIFNG = 0.0
      DIFPS = 0.0
      DO 7777 I = 1,INDX
         DIFFI = DIFF(I)  * DELT(I)
         IF( DIFFI.LT.0.0 )  DIFNG = DIFNG+DIFFI
         IF( DIFFI.GT.0.0 )  DIFPS = DIFPS + DIFFI
 7777 CONTINUE
      DIFNG =-DIFNG
      WRITE(6,8)
      WRITE(6,3)(T(I),SAT(I),SURF(I),SUM(I),
     *           DELT(I),DEF(I),SURFR(I),SUMR(I),DIFF(I),QK(I),I=1,INDX)
      I = INDX + 1
      WRITE(6,3) T(I),        SAT(I),SURF(I),SUM(I)
      CALL          SHUFLF
      CALL       RESP( INC1,INC2,SR,SS,MA,MP )
      WRITE(6,12)  MA,MP ,T(INC1),T(INC2)
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      WRITE(6,13)
      WRITE(6,2)    (T(I),DELT(I),QK(I)   ,I=1,INDX)
      CALL        AREA( VAR,HAR,RATIO,XPRO,INC1,INC2)
      WRITE(6,7)  VAR,DIFPS,HAR,DIFNG,XPRO,RATIO,QAVR,(TYPE(J,KT),J=1,6)
      IF(NPUNCH.EQ.1) CALL PNCH(VAR,HAR,RATIO,XPRO,DIFPS,DIFNG)
      IF(NPLT.EQ.1) CALL PLT(SR,SS,TITLE)
 8888 IF(ST+SUB+MO+DY+YR) 11111,11110,11111
      END
      SUBROUTINE   CALCK(  SR,SS,RATE,SETVAL,BOUND,QAVR,KT     )
C     CALCK...THIS SUBROUTINE DETERMINES THE DIFFUSION CONSTANT(K) FOR MONTH MO
C         AND DAY DY.  IF SETVAL IS GIVEN AS AN INPUT ARGUMENT, THE VALUE OF
C         SETVAL WILL BE USED FOR THE ENTIRE DATA SET.  IF SETVAL IS OMITTED,
C         RATE(MO,DY) WILL BE USED FOR DATE MO,DY IF GIVEN ON THE SR-SS CARD
C         FOR DATE MO,DY.  IF BOTH SETVAL AND RATE(MO,DY) ARE OMITTED, CALCK
C         WILL DETERMINE THE ATMOSPHERIC DIFFUSION CONSTANT BY AVERAGING THE
C         K VALUES CALCULATED BETWEEN EACH PAIR OF NIGHTTIME OXYGEN
C         RATES-OF-CHANGE AND SURFACE SATURATION DEFICITS.
      COMMON /CAL/  SURFR,DEF
      COMMON T,QK,DELT,INDX,MARK,IERROR
      DIMENSION   T(100),QK(100),DELT(100),SURFR(100),DEF(100)
      IF(ABS(SETVAL).LE. 0.0   )  GO TO 1
      KT = 2
      QAVR = SETVAL
      RETURN
    1 IF( ABS(RATE).LE.0.0 )  GO TO 5
      KT = 3
      QAVR = RATE
      RETURN
    5 QSUM=0.0
      KT = 1
      QKNT=0.0
      I=1
   10 IF(T(I).GE.SR) GO TO 30
      GO TO 20
   15 IF(DEF(I).EQ.DEF(I+1)) GO TO 17
      IF(DEF(I).EQ.DEF(I+1))GO TO 16
      QVAL=-ABS((SURFR(I+1)-SURFR(I))/(DEF(I+1)-DEF(I)))
   16 IF(ABS(QVAL).GT.ABS(BOUND).OR.DEF(I).EQ.DEF(I+1)) QVAL=-ABS(BOUND)
      QSUM=QSUM+QVAL
      QKNT=QKNT+1.0
   17 I=I+1
      IF(I.EQ.INDX) GO TO 50
   20 IF(T(I+1).LE.SR ) GO TO 15
   25 I=I+1
      IF(I.EQ.INDX) GO TO 50
   30 IF(T(I).LT.SS) GO TO 25
   40 IF(T(I+1).LE.SS) GO TO 20
      IF(DEF(I).EQ.DEF(I+1)) GO TO 45
      IF(DEF(I).EQ.DEF(I+1))GO TO 42
      QVAL=-ABS((SURFR(I+1)-SURFR(I))/(DEF(I+1)-DEF(I)))
   42 IF(ABS(QVAL).GT.ABS(BOUND).OR.DEF(I).EQ.DEF(I+1)) QVAL=-ABS(BOUND)
      QSUM=QSUM+QVAL
      QKNT=QKNT+1.0
   45 I=I+1
      IF(I.LT.INDX) GO TO 40
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   50 QAVR=-ABS(QSUM/QKNT)
      RETURN
      END
      SUBROUTINE    SHUFLE
C     SHUFLE...THIS SUBROUTINE REORGANIZES INPUT DATA, SO READINGS WILL BEGIN
C          AT TIME 0.00 AND END AT TIME 24.00.
      COMMON T,QK,DELT,INDX,MARK,IERROR
      DIMENSION T(100),SURF(100),SAT(100),QK(100),DELT(100),Q(100)
      DELT(INDX) = T(1 ) - T(INDX)
      MINDX = INDX + 2 -MARK
      SURF(1)= 0.0
      Q(1) = QK(MARK-1)
      SAT(1) = T(MARK)
      DO 1111  I = 2,MINDX
         MARI = MARK + I    -2
         Q(I) = QK(MARI)
         SURF(I) = T(MARI)
         SAT(I) = DELT(MARI)
 1111 CONTINUE
      MRKM1 = MARK - 1
      DO2222 I = 1,MRKM1
         MI = MINDX+I
         Q(MI) = QK(I)
         SURF(MI) = T(I)
         SAT(MI) = DELT(I)
 2222 CONTINUE
      INDX = INDX + 2
      SURF(INDX) = 24.0
      SAT(INDX-1) = 24.0 -SURF(INDX-1)
      SAT(INDX) = 0.0
      Q(INDX) = Q(INDX-1)
      DO 3333 I = 1,INDX
         QK(I) = Q(I)
         T(I) = SURF(I)
         DELT(I) = SAT(I)
 3333 CONTINUE
      DO 140 I = 1,INDX
         II = INDX + 1-I
         IF(T(II).LE.12.0  ) GO TO 145
         QK(II+1) = QK(II)
         T(II+1) = T(II)
         DELT(II+1) = DELT(II)
  140 CONTINUE
  145 MARK = II+1
      DELT(1) = T(2)
      T(MARK ) = 12.0
      DELT(MARK) = T(MARK+1)-12.0
      QK(MARK) = QK(MARK-1)
      DELT(MARK-1) = 12.0 -T(MARK-1)
      INDX = INDX+1
      RETURN
      END
      SUBROUTINE RESP( INC1,INC2,SR,SS,MA,MP )
C     RESP...THIS SUBROUTINE DECIDES WHICH PRE-SUNRISE AND POST-SUNSET POINTS ON
C          THE NEGATIVE RATE-OF-CHANGE CURVE WILL BE USED TO CALCULATE THE
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C         HYPOTHETICAL DAYTIME RESPIRATION LINE.
      COMMON T,QK,DELT,INDX,MARK,IERROR
      DIMENSION T(100),QK(100),DELT(100)
      MIN1 =  1
      MRKM1 = MARK-1
      DO 150 I = 1,MRKM1
         IF(QK(I).LE.QK(MIN1))   MIN1 = I
  150 CONTINUE
      IF(QK(MIN1) .GT.0.0 ) CALL ERROR(      2                    )
      DO 170 I = 1,MARK
      IF(T(I).GT.SR) GO TO 180
  170 CONTINUE
  180 II = I-1
      IPBSR = II
      IF(MIN1.LT.IPBSR) GO TO 185
      MA = 1
      INC1 = MIN1 + 1
      GO TO 230
  185 IF((SR-T(IPBSR))/DELT(IPBSR).LT. .75 ) GO TO 190
      IF(QK(IPBSR).GE.0.0 ) GO TO 190
      INC1 = IPBSR+1
      MA = 2
      GO TO 230
  190 CONTINUE
      MA = 3
      DO 200 I = 1,IPBSR
         II = IPBSR-I
         IF(QK(II).LT. 0.0 ) GO TO 210
  200 CONTINUE
  210 IP1 = II
      T(IPBSR) = SR
      DELT(IPBSR-1) = SR-T(IPBSR-1)
      DELT(IPBSR) = T(IPBSR+1) - SR
      IPBSR1 = IPBSR-1
      DO 220 I = IP1,IPBSR1
         QK(I) = QK(IP1)
  220 CONTINUE
      INC1 = IPBSR
  230 CONTINUE
      DO 240 I = MARK,INDX
         IF( SS.LT.T(I)) GO TO 250
  240 CONTINUE
  250 IPASS = I
      INC2 = I
      IF((T(IPASS)-SS)/DELT(IPASS-1).GE. .5)   INC2 = INC2-1
      LIMIT = INDX
      IF(INDX-INC2.GE.2) LIMIT=INC2+2
      MIN2 = LIMIT
      DO 160 I=MARK,LIMIT
      IF( QK(I).LT.QK(MIN2)) MIN2 = I
  160 CONTINUE
      IF(QK(MIN2) .GT.0.0 ) CALL ERROR(      3                    )
  260 IF(MIN2.GT.INC2) GO TO 270
      MP = 1
      INC2 = MIN2
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      GO TO 310
  270 CONTINUE
      MP = 2
      DO 300 I = IPASS,MIN2
         QK(I) = QK(MIN2)
  300 CONTINUE
      INC2 = IPASS
  310 CONTINUE
      RETURN
      END
      SUBROUTINE  AREA( VAR,HAR,RATIO,XPRO,INC1,INC2)
C     AREA...THIS SUBROUTINE INTEGRATES APPROPRIATE SECTIONS OF THE
C         RATE-OF-CHANGE CURVE TO YEILD GROSS PRIMARY PRODUCTIVITY(VAR) AND
C         COMMUNITY RESPIRATION(HAR), AND COMPUTES NET PRODUCTVITY(XPRO) AND
C         P/R RATIO(RATIO).
      COMMON T,QK,DELT,INDX,MARK,IERROR
      DIMENSION  T(100) , QK(100) , DELT(100)
      INC1M1 = INC1-1
      AR = 0.0
      INC2M1 = INC2 - 1
      DO 100 I = INC1,INC2M1
         AR = AR + QK(I)*DELT(I)
  100 CONTINUE
      ART = (QK(INC1-1)+QK(INC2))*(T(INC2)-T(INC1))/2.0
      VAR = AR - ART
      HAR = 0.0
      DO 300 I=1,INC1M1
         IF( QK(I).LT.0.) HAR = HAR + QK(I)*DELT(I)
  300 CONTINUE
      DO 400 I = INC2,INDX
         IF( QK(I).LT.0.) HAR = HAR + QK(I)*DELT(I)
  400 CONTINUE
      HAR = -(ART+HAR)
      XPRO = VAR-HAR
      RATIO = VAR/HAR
      RETURN
      END
      SUBROUTINE   PLT(SR,SS,TITLE)
      COMMON/HEAD/ST1,SUB1,MO1,DY1,YR1
C     PLT...THIS SUBROUTINE PLOTS CORRECTED DISSOLVED OXYGEN RATE-OF-CHANGE
C         (G/M**2/HR) VERSUS TIME IN HOURS.  PLT IS OPTIONAL AS SPECIFIED BY
C         INPUT ARGUMENT NPLT.
      COMMON T,QK
      DIMENSION  T(100),QK(100)
      DIMENSION TX(250),QY(250),DUM(250),TITLE(20)
      INTEGER  ST1,SUB1,MO1,DY1,YR1
      DO 776 I=1,250
         TX(I) = 0.0
         QY(I) = 0.0
  776 CONTINUE
      TX(1)=T(1)
      QY(1)=QK(1)
      J = 1
      DO 778 I=1,241
         TX(I+1) = TX(I) + .1
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         IF( TX(I+1).GE.T(J+1))  J = J+1
         QY(I+1) = QK(J)
  778 CONTINUE
       TX(242) = SR
      QY(242) = 0.0
       TX(243) = SS
      QY(243) = 0.0
      TX(244) = -.32
      QY(244) = 0.0
      TX(245) =24.32
      QY(245) = 0.0
      CALL PLOT(TX,0,QY,0,DUM,0,243,1,1,0,2,0,1)
      WRITE(6,2)
      WRITE(6,1)  TITLE,ST1,SUB1,MO1,DY1,YR1
      WRITE(6,3)  SR,SS
    1 FORMAT(1H ,20A4,8HSTATION ,I2,3X,11HSUBSTATION ,I2,3X,5HDATE ,I2,1
     *H/,I2,1H/,I2  ,//)
    2 FORMAT(1H0,10X,'Y-AXIS = RATE OF CHANGE IN GRAMS-OF-OXYGEN/M**2/HOUR
     *UR',30X,'X-AXIS = TIME IN HOURS')
    3 FORMAT(82X,'SUNRISE=',F5.2,5X,'SUNSET=',F5.2)
      RETURN
      END
      SUBROUTINE          PNCH(VAR,HAR,RATIO,XPRO,DIFPS,DIFNG)
      COMMON/HEAD/ST1,SUB1,MO1,DY1,YR1
C     PNCH...THIS SUBROUTINE PUNCHES OUTPUT ON CARDS.  PNCH IS OPTIONAL AS
C         SPECIFIED BY INPUT ARGUMENT NPUNCH.
      ISCVAR = (100.*ABS(     VAR         )) + .5
      IHAR   = (100.*ABS(     HAR         )) + .5
      IXPRO  = (100.*ABS(     XPRO        )) + .5
      IRATI  = (100.*ABS(     RATIO       )) + .5
      IDIFP  = (100.*ABS(     DIFPS       )) + .5
      IDIFN  = (100.*ABS(     DIFNG       )) + .5
      WRITE(7,4) ST1,SUB1,YR1,MO1,DY1,ISCVAR,IHAR,IXPRO,IRATI,IDIFP,
     *   IDIFN
    4 FORMAT(6X,2H14,2I2,3I3,4X,2I10,4I5    )
      RETURN
      END
      SUBROUTINE ERROR(M)
      GO TO (1,2,3),M
    1 WRITE(6,11)M
      RETURN
    2 WRITE(6,22)
      RETURN
    3 WRITE(6,33)
      RETURN
   11 FORMAT(1H0, 12H***** ERROR    ,I2,17H OCCURRED *****      ,/
     *   1H ,37H***** SKIP TO NEXT DATA SET *****   ////)
   22 FORMAT(1H ,38H***** AM VALUES ARE ALL POSITIVE *****         )
   33 FORMAT(1H ,38H***** PM VALUES ARE ALL POSITIVE *****         )
      END
      SUBROUTINE PLOT(X,LX,Y,LY,Z,LZ,NPT,NPLOT,NCOPY,NCD,NDIM,NXTREM,
     *NPAGE)
C   PURPOSE
C     THIS SUBROUTINE PLOTS UP TO TEN RELATIONSHIPS OF THE FORM Y = F(X).
C     IT WILL ALSO PREPARE TOPOGRAPHIC MAPPINGS OF THREE DIMENSIONAL
```

```
C      SURFACES.
C    USAGE
C      CALL PLOT(X,LX,Y,LY,Z,LZ,NPT,NPLOT,NCOPY,NCD,NDIM,NXTREM,NPAGE)
C      X, Y, Z - COORDINATES OF DATA POINTS
C      LX, LY, LZ - SCALING FACTORS.  THE SCALES ON EACH AXIS MAY BE LINEAR,
C            ONE CYCLE LOG, TWO CYCLE LOG, ...SIX CYCLE LOG
C      NPT - NUMBER OF POINTS TO BE PLOTTED
C      NPLOT  - NUMBER OF RELATIONSHIPS TO BE PLOTTED IN DIFFERENT
C            SYMBOLS IF PLOTS ARE TWO DIMENSIONAL.  IF A TOPOGRAPHIC
C            MAPPING IS CALLED FOR NPLOT IS NUMBER OF CONTOURS TO BE PLOTTED.
C      NCOPY - NUMBER OF DUPLICATE PLOTS TO BE MADE
C      NCD - NUMBER OF INFORMATION CARDS TO BE READ.  IF NCD IS ZERO NO
C            CARDS ARE READ.  OTHERWISE SEE WRITE UP.
C      NDIM - IF THE RELATIONSHIPS WHICH ARE TO BE PLOTTED ARE TWO
C            DIMENSIONAL NDIM IS 2, AND IF A TOPOGRAPHICH MAPPING IS DESIRED
C            NDIM IS 3.
C      NXTREM - IF NXTREM IS 1, A CARD WITH THE LIMITING VALUES OF
C            THE X, Y, AND Z SCALES IS READ.  OTHERWISE THEY ARE
C            CALCULATED WITHIN THE SUBROUTINE SO THAT ALL DATA POINTS WILL
C            APPEAR ON THE PLOT.
C      NPAGE - NUMBER OF PAGES THE PLOT IS TO COVER.  IF NPAGE IS 1 THE PLOT
C            IS 50 LINES HIGH.  EACH INCREASE OF 1 IN NPAGE CAUSES THE
C            PLOT TO EXTEND ACROSS AN ADDITIONAL 66 LINES.
C    SUBROUTINES REQUIRED
C      THE FORTRAN IV SUBROUTINE POT IS INCLUDED AS PART OF THE
C      PLOTTING PACKAGE.
C
       REAL N
       DIMENSION X(1),Y(1),Z(1),SX(7),TITLE(20),L(134),NCH(41),NH(41)
      *,MOP(42),FM1(6),FM2(6),FM3(6),FM4(8),FM5(8),FM6(8),FMT(6),FRT(8)
      1,SCL(3)
       DATA FM1/'(1H ',',A1,','F9.2',',121','A1) ',' '/
       DATA FM2/'(1H ',',A1,','F9.4',',121','A1) ',' '/
       DATA FM3/'(1H ',',A1,','1PE9','.2,1','21A1',')  '/
       DATA FM4/'(1X,','1PE1','6.2,','5E20','.2,E','15.2',')   ',' '/
       DATA FM5/'(5X,','F9.4',',5(1','1X,F','9.4)',',9X,','F9.4',')   '/
       DATA FM6/'(5X,','F9.2',',5(1','1X,F','9.2)',',9X,','F9.2',')   '/
       DATA NCH/1H0,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,1HA,1HB,1HC,1HD,
      *1HE,1HF,1HG,1HH,1HI,1HJ,1HK,1HL,1HM,1HN,1HO,1HP,1HQ,1HR,1HS,1HT, 1
      *HU,1HV,1HW,1HX,1HY,1H0,1H*,1H$,1H=,1H+,1H-/
       DATA ND,NP,NM,NB/1H.,1H+,1H-,1H /
       DATA SCL/1HX,1HY,1HZ/
1      FORMAT(20A4)
     2 FORMAT(52A1,7A4)
3      FORMAT(1H ,26X,20A4)
5      FORMAT(132A1)
     6 FORMAT(5H ALL ,A1,57H VALUES ARE NEGATIVE.  LOG SCALE MAY NOT BE S
      *PECIFIED.                )
     7 FORMAT(1PE17.2,E115.2)
     8 FORMAT(1PE17.2,E61.2,E54.2)
     9 FORMAT(1PE17.2,2E40.2,E35.2)
    10 FORMAT(1PE17.2,3E30.2,E25.2)
    11 FORMAT(1PE17.2,4E24.2,E19.2)
    12 FORMAT(1HK,59X,7A4)
    74 FORMAT(6E12.2)
```

```
   76 FORMAT(1H1)
   80 FORMAT(70H NPT(NO. OF PTS.) MUST BE EVENLY DIVISIBLE BY NPLOT(NO.
     *OF CURVES.)                        )
   84 FORMAT(1X,36HONE DIMENSIONAL PLOT NOT ALLOWED.       )
   94 FORMAT(42A1,10X,7A4)
      DO95I=1,41
   95 NH(I)=NCH(I)
      N=50+66*(NPAGE-1)
      LLX=LX+1
      NDD=NCD+1
        GOTO(15,13,14,13),NDD
13     READ(5,1)(TITLE(I),I=1,20)
   14 IF(NDD.LT.3)GOTO15
      IF(NDIM.NE.3)GOTO93
      READ(5,94)(MOP(I),I=1,42),TAB1,TAB2,TAB3,TAB4,TAB5,TAB6,TAB7
      GO TO 81
   93 READ(5,2)(MOP(I),I=1,42),( NH(I),I=1,10),TAB1,TAB2,TAB3,TAB4,TAB5,
     1TAB6,TAB7
      GOTO81
   15 DO82I=1,42
   82 MOP(I)=NB
   81 NCH(41)=NB
      IF(FLOAT(NPT/NPLOT)-FLOAT(NPT)/FLOAT(NPLOT))101,85,101
  85  IF(NXTREM.EQ.1)GOTO72
      YMIN=1.00E 75
      XMIN=YMIN
      ZMIN=YMIN
      YMAX=1.00E-78
      XMAX=YMAX
      ZMAX=YMAX
      DO51I=1,NPT
      GOTO(103,52,53),NDIM
   53 IF(Z(I).GE.ZMAX)ZMAX=Z(I)
      IF(Z(I).LE.ZMIN)ZMIN=Z(I)
   52 IF(Y(I).GE.YMAX)YMAX=Y(I)
      IF(Y(I).LE.YMIN)YMIN=Y(I)
      IF(X(I).GE.XMAX)XMAX=X(I)
      IF(X(I).LE.XMIN)XMIN=X(I)
   51 CONTINUE
      IF(LX.GT.0)GOTO900
      XMIN=XMIN-(XMAX-XMIN)/75.0
      XMAX=XMAX+(XMAX-XMIN)/75.0
  900 IF(LY.GT.0)GOTO73
      YMIN=YMIN-(YMAX-YMIN)/30.0
      YMAX=YMAX+(YMAX-YMIN)/30.0
      GOTO73
   72 READ(5,74)XMIN,XMAX,YMIN,YMAX,ZMIN,ZMAX
   73 IF(YMAX.GT.10000.0.OR.YMIN.LT.(-10000.0))GOTO60
      IF (YMAX-YMIN.LT.5.0)GOTO60
      IF(YMAX.GT.10.0.OR.YMIN.LT.(-10.0))GOTO62
      IF(YMAX.LT.0.01.OR.ABS(YMIN).LT.0.01)GOTO60
      DO59I=1,6
   59 FMT(I)=FM2(I)
      GOTO65
   60 DO61I=1,6
```

```
61 FMT(I)=FM3(I)
   GOTO65
62 DO63I=1,6
63 FMT(I)=FM1(I)
65 IF(XMAX.GT.10000.0.OR.XMIN.LT.(-10000.0))GOTO67
   IF(XMAX-XMIN.LT.5.0)GOTO67
   IF(XMAX.GT.10.0.OR.XMIN.LT.(-10.0))GOTO69
   IF(XMAX.LT.0.01.OR.ABS(XMIN).LT.0.01)GOTO67
   DO66I=1,8
66 FRT(I)=FM5(I)
   GOTO70
67 DO68I=1,8
68 FRT(I)=FM4(I)
   GOTO70
69 DO71I=1,8
71 FRT(I)=FM6(I)
70 IF(LX.GT.0)GOTO17
   CX=120./(XMAX-XMIN)
   SX(1)=XMIN
   SX(7)=XMAX
   U=XMIN
   DO16K=2,6
   U=(XMAX-XMIN)/6.+U
16 SX(K)=U
   GOTO19
17 XLX=LX
   IF(XMAX.LE.0.0)GOTO100
   XMIN=10.0**(ALOG10(XMAX*9.999999)-FLOAT(LX))
   MS=1
   CX=120./XLX
   NX=ALOG10(XMIN)
   IF(XMIN.LT.1.0)NX=ALOG10(XMIN)-0.9999999
   XMIN=10.0**NX
   DO18K=1,LLX
18 SX(K)=10.**(NX+K-1)
19 CALLPOT(X,XMIN,LX,NPT,0,120.,CX)
   IF(LY.GT.0)GOTO20
   CY=N/(YMAX-YMIN)
   GOTO21
20 YLY=LY
   IF(YMAX.LE.0.0)GOTO100
   YMIN=10.0**(ALOG10(YMAX*9.999999)-FLOAT(LY))
   MS=2
   CY=N/YLY
   KY=CY
   NY=ALOG10(YMIN)
   IF(YMIN.LT.1.0)NY=ALOG10(YMIN)-0.9999999
   YMIN=10.0**NY
21 CALLPOT(Y,YMIN,LY,NPT,1,N,CY)
   IF(NDIM.LT.3)GOTO24
   FPLOT=NPLOT
   IF(LZ.GT.0)GOTO22
   CZ=FPLOT/(ZMAX-ZMIN)
   GOTO23
22 ZLZ=LZ
```

```
      IF(ZMAX.LE.0.0)GOTO100
      ZMIN=10.0**(ALOG10(ZMAX*9.999999)-ZLZ)
      MS=3
      CZ=FPLOT/ZLZ
      IF(ZMIN.GE.1.0)GO TO 23
      IA=ALOG10(ZMIN)-.9999999
      ZMIN=10.0**IA
   23 CALL POT(Z,ZMIN,LZ,NPT,0,FPLOT,CZ)
      DO77I=1,NPT
      IZ=Z(I)+1.0
      Z(I)=NCH(IZ)
   77 CONTINUE
      GOTO99
   24 NPN=NPT/NPLOT
      DO 78I=1,NPLOT
      JJ=(I-1)*NPN+1
      JK=I*NPN
      DO78J=JJ,JK
      Z(J)=NH(I)
   78 CONTINUE
   99 DO102I=1,NPT
      DO102J=I,NPT
      IF(Y(I).GE.Y(J))GOTO102
      A=Y(I)
      B=X(I)
      Y(I)=Y(J)
      X(I)=X(J)
      Y(J)=A
      X(J)=B
      C=Z(I)
      Z(I)=Z(J)
      Z(J)=C
  102 CONTINUE
      DO56NO=1,NCOPY
      M1=1
      M2=1
      LL=0
      LYY=LY
      TT=N
      WRITE(6,76)
      IF(NOD.EQ.1.OR.NOD.EQ.3)GO TO 97
      WRITE(6,3)(TITLE(I),I=1,20)
   97 NN=N+1.0
      DO43KK=1,NN
      M=1
      NNN=NPN
      JED=1
      T=INT(N)-KK+1
      DO25J=1,133
   25 L(J)=NB
      L(133)=ND
      IF(LY.GT.0)GOTO026
      L(13)=NP
      IF(T.GT.TT)GOTO030
      SCALE=T/CY+YMIN
```

```
      L(133)=NP
      M=0
      TT=TT-5.
      IF(T.LE.0.)SCALE=YMIN
      GOTO30
   26 GOTO(27,27,28,28,27,28),LY
   27 SS=KY*LYY
      GOTO29
   28 SS=KY*LYY+1
   29 L(13)=ND
      IF(T.GT.SS)GOTO30
      SCALE=10.**(NY+LYY)
      M=0
      LYY=LYY-1
      L(13)=NP
      L(133)=NP
   30 IF(N.EQ.T)GOTO31
      IF(0..NE.T)GOTO37
   31 DO32J=14,133
   32 L(J)=NM
      IF(LX.GT.0)GOTO34
      DO33J=13,133,10
   33 L(J)=NP
      GOTO36
   34 KX=120/LX
      DO35J=13,133,KX
   35 L(J)=NP
   36 IF(N.EQ.T)L(133)=ND
   37 LL=LL+1
      IF(LL.GT.NPT)GOTO79
      IF(Y(LL)-T)79,92,37
   92 J=X(LL)
      L(J+13)=Z(LL)
      GOTO37
   79 LL=LL-1
      IF(M1.GT.4+( INT(N)-50)/2  .AND.M1.LT.47+( INT(N)-50)/2  )GOTO54
      L(2)=NB
      GOTO55
   54 L(2)=MOP(M2)
      M2=M2+1
   55 M1=M1+1
   41 IF(M.EQ.1)GOTO42
      WRITE(6,FMT)L(2),SCALE,(L(J),J=13,133)
      GOTO43
42    WRITE(6,5)(L(J),J=1,11),(L(J),J=13,133)
   43 CONTINUE
      GOTO(44,45,46,47,48,49,44),LLX
   44 WRITE(6,FRT)(SX(K),K=1,7)
      GOTO50
   45 WRITE(6,7)(SX(K),K=1,LLX)
      GOTO50
   46 WRITE(6,8)(SX(K),K=1,LLX)
      GOTO50
   47 WRITE(6,9)(SX(K),K=1,LLX)
      GOTO50
```

```
 48 WRITE(6,10)(SX(K),K=1,LLX)
    GOTO50
 49 WRITE(6,11)(SX(K),K=1,LLX)
 50 IF(NDD.LT.3)GOTO56
    WRITE(6,12)TAB1,TAB2,TAB3,TAB4,TAB5,TAB6,TAB7
 56 CONTINUE
 83 RETURN
100 WRITE(6,6)SCL(MS)
    RETURN
101 WRITE(6,80)
    RETURN
103 WRITE(6,84)
    RETURN
    END
    SUBROUTINEPOT(V,VMIN,LV,NP,J,VC,C)
    DIMENSIONV(1)
    IF(LV.GT.0)GOTO2
    DO1I=1,NP
  1 V(I)=FLOAT( INT(C*(V(I)-VMIN)+.5))
     GOTO4
  2 VMIN=10.0**( INT(ALOG10(VMIN)))
    DO3I=1,NP
    IF(V(I).LE.0.0)GOTO3
    V(I)=FLOAT( INT(C*(ALOG(V(I)/VMIN)/2.302585)+.5))
    VT=V(I)
  3 CONTINUE
  4 DO6I=1,NP
    IF(V(I).LT.0.)GOTO5
    IF(V(I).LE.VC)GOTO6
  5 V(I)=VC+1.
  6 CONTINUE
    RETURN
    END
```

```
                                   DEFINITION  OF  CLASSES  OF  DATA
                                                   FOR
                    PLACEMENT  OF  ENDPOINTS  OF  THE  HYPOTHETICAL  DAYLIGHT  RESPIRATION  LINE

MORNING CLASSES
          CLASS(1,X)...IF  MINIMUM MORNING INTERVAL IS BETWEEN INTERVAL NEAREST SUNRISE AND NOON,
                       RESPIRATION LINE WILL BE DRAWN FROM THE LEADING EDGE OF THE  MINIMUM INTERVAL
          CLASS(2,X)...IF THE MINIMUM INTERVAL OCCURS BEFORE THE INTERVAL NEAREST SUNRISE AND IF LESS THAN 25 PERCENT OF
                       THE INTERVAL CONTAINING SUNRISE IS LIGHT AND THE SR INTERVAL IS NEGATIVE, THE LINE WILL BE DRAWN
                       FROM THE RIGHT EDGE OF THE SR INTERVAL.
          CLASS(3,X)...IF MORE THAN 25 PERCENT OF THE SR INTERVAL IS LIGHT OR IF THE SR INTERVAL IS POSITIVE, THE RATE OF
                       THE FIRST PRECEDING NEGATIVE INTERVAL WILL BE EXTENDED TO SR AND THE LINE WILL BE DRAWN FROM THAT
                       POINT.
EVENING POINT
          CLASS(X,1)...IF THE EVENING MINIMUM INTERVAL OCCURS BETWEEN NOON AND THE INTERVAL NEAREST SUNSET, THE LINE WILL
                       BE DRAWN TO THE LEFT EDGE OF THE MINIMUM INTERVAL.
          CLASS(X,2)...IF THE MINIMUM INTERVAL OCCURS AFTER THE INTERVAL NEAREST SS, THE RATE OF THE MINIMUM INTERVAL WILL
                       BE EXTENDED BACK TO THE RIGHT EDGE OF THE INTERVAL CONTAINING SS AND THE LINE WILL BE DRAWN TO THAT
                       POINT.
```

```
   1    1     1 10.00
   6   21       5.55      19.63
                          ROSHANARA GARDEN TANK   DELHI, INDIA
 (          8X,2I2,3I3,4X,F5.2,F4.2,F6.1,F7.1 )
     12 1 1 59  6 21  1 09.00  72    5.3     5.3
     12 1 1 59  6 21  1 12.00 178   12.5    12.5
     12 1 1 59  6 21  1 15.00 406   28.2    28.2
     12 1 1 59  6 21  1 18.00 206   14.8    14.8
     12 1 1 59  6 21  1 21.00 103    7.6     7.6
     12 1 1 59  6 21  1 00.00  70    5.3     5.3
     12 1 1 59  6 21  1 03.00  18    1.4     1.4
     12 1 1 59  6 21  1 06.00   1    0.1     0.1
     12 1 1 59  6 21  1 09.00  34    2.4     2.4

   3    1     1 10.00
  11   24       6.97      17.45
   2   27       6.97      18.43
   4    3       6.32      18.85
                          KADEL POND, ST. PETERSBURG, FLORIDA
 (          8X,2I2,3I3,4X,F5.2,F4.2,F6.1,F7.1 )
     12 1 1 67  4  3  3 07.00  80    7.3    21.3
     12 1 1 67  4  3  3 11.00  83    7.4    21.6
     12 1 1 67  4  3  3 15.00  95    8.1    22.3
     12 1 1 67  4  3  3 19.00 103    8.9    24.8
     12 1 1 67  4  3  3 23.00  92    8.1    23.2
     12 1 1 67  4  3  3 03.00  85    7.6    22.2
     12 1 1 67  4  3  3 07.00  80    7.3    21.3
```

```
                                         KADEL  POND,  FLORIDA
                                 STATION  1     SUBSTATION  1     DATE  4/ 3/67

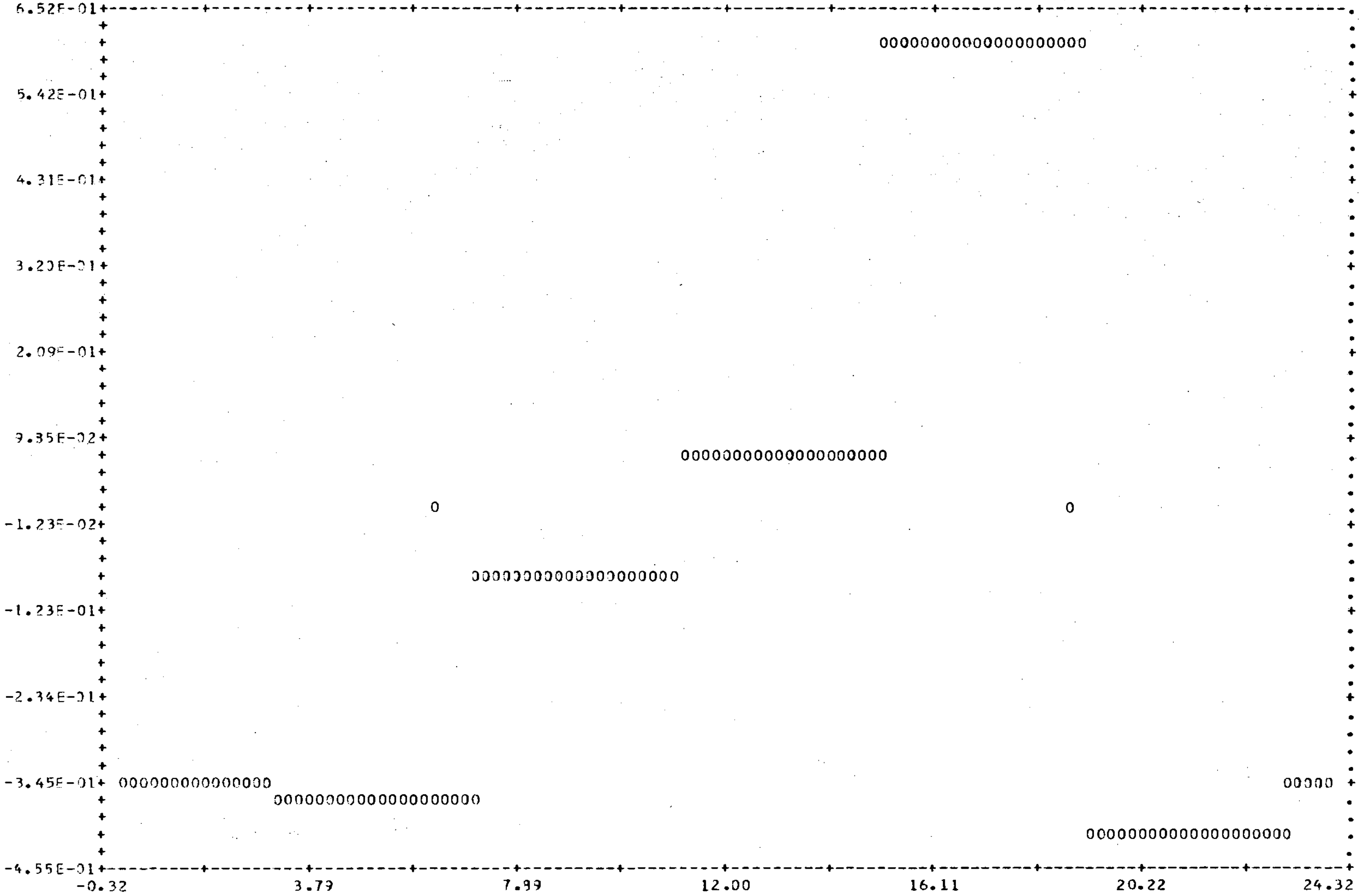

 TIME    INTERVAL          SURFACE     SAT          SURFACE    SURF RT         COLUMN    COL RT      DIFF    CORR RATE
  HR        HR               SAT       DEF          G/M**3    G/M**3/HR        G/M**2  G/M**2/HR     CORR    G/M**2/HR
  7.00                      0.80                      7.3                        21.3
            4.00                      0.19                       0.03                      0.08      -0.15    -0.079
 11.00                      0.83                      7.4                        21.6
            4.00                      0.11                       0.17                      0.17      -0.09     0.083
 15.00                      0.95                      8.1                        22.3
            4.00                      0.01                       0.20                      0.63      -0.01     0.617
 19.00                      1.03                      8.9                        24.8
            4.00                      0.03                      -0.20                     -0.40      -0.02    -0.421
 23.00                      0.92                      8.1                        23.2
            4.00                      0.12                      -0.13                     -0.25      -0.10    -0.346
  3.00                      0.85                      7.6                        22.2
            4.00                      0.18                      -0.08                     -0.23      -0.15    -0.371
  7.00                      0.80                      7.3                        21.3


VALUES ADJUSTED ACCORDING TO CLASS(1,1)
RESPIRATION LINE BEGINS AT      7.00 HOURS  AND ENDS  AT      19.00HOURS

      TIME   INTERVAL       RATE

       0.0      3.00      -0.35
       3.00     4.00      -0.37
       7.00     4.00      -0.08
      11.00     1.00       0.08
      12.00     3.00       0.08
      15.00     4.00       0.62
      19.00     4.00      -0.42
      23.00     1.00      -0.35
      24.00     0.0       -0.35

GROSS PROD =        7.23  G OF O2/M**2/24HR          DIFFUSION-OUT =    0.0   G OF O2/M**2/24HR
TOTAL RESP =        9.30  G OF O2/M**2/24HR          DIFFUSION-IN  =    2.07  G OF O2/M**2/24HR
NET PROD   =       -2.07  G OF O2/M**2/24HR
PROD/RESP  =        0.78                             DIFFUSION CONSTANT (K)  =  -0.83  CALCULATED BY AVERAGING
```



Y-AXIS = RATE OF CHANGE IN GRAMS-OF-OXYGEN/M**2/HOUR
KADEL POND, FLORIDA

X-AXIS = TIME IN HOURS
STATION 1 SUBSTATION 1 DATE 4/ 3/67

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                         A  SHALLOW  POND  IN  DELHI,  INDIA
                      STATION  1     SUBSTATION  1     DATE  6/21/59

     TIME   INTERVAL       SURFACE     SAT         SURFACE   SURF RT         COLUMN    COL RT     DIFF    CORR RATE
      HR       HR            SAT       DEF         G/M**3   G/M**3/HR        G/M**2  G/M**2/HR    CORR    G/M**2/HR
     9.00                   0.72                      5.3                      5.3
             3.00                    -0.25                     2.40                        2.40     0.47      2.871
    12.00                   1.78                     12.5                     12.5
             3.00                    -1.92                     5.23                        5.23     3.62      8.850
    15.00                   4.06                     28.2                     28.2
             3.00                    -2.06                    -4.47                       -4.47     3.88     -0.587
    18.00                   2.06                     14.8                     14.8
             3.00                    -0.54                    -2.40                       -2.40     1.03     -1.374
    21.00                   1.03                      7.5                      7.6
             3.00                     0.14                    -0.77                       -0.77    -0.25     -1.021
     0.0                    0.70                      5.3                      5.3
             3.00                     0.56                    -1.30                       -1.30    -1.05     -2.355
     3.00                   0.18                      1.4                      1.4
             3.00                     0.91                    -0.43                       -0.43    -1.70     -2.138
     6.00                   0.01                      0.1                      0.1
             3.00                     0.83                     0.77                        0.77    -1.55     -0.787
     9.00                   0.34                      2.4                      2.4

    VALUES ADJUSTED ACCORDING TO CLASS(2,1)
    RESPIRATION LINE BEGINS AT      6.00 HOURS  AND ENDS  AT      18.00HOURS

        TIME  INTERVAL      RATE

         0.0      0.0      -1.02
         0.0      3.00     -2.35
         3.00     3.00     -2.14
         6.00     3.00     -0.79
         9.00     3.00      2.87
        12.00     0.0       8.85
        12.00     3.00      8.85
        15.00     3.00     -0.59
        18.00     3.00     -1.37
        21.00     3.00     -1.02
        24.00     0.0      -1.02

   GROSS PROD =       52.11  G OF O2/M**2/24HR          DIFFUSION-OUT =   26.98  G OF O2/M**2/24HR
   TOTAL RESP =       41.73  G OF O2/M**2/24HR          DIFFUSION-IN  =   13.70  G OF O2/M**2/24HR
   NET PROD   =       10.38  G OF O2/M**2/24HR
   PROD/RESP  =        1.25                             DIFFUSION CONSTANT (K)  =  -1.88  CALCULATED BY AVERAGING
```

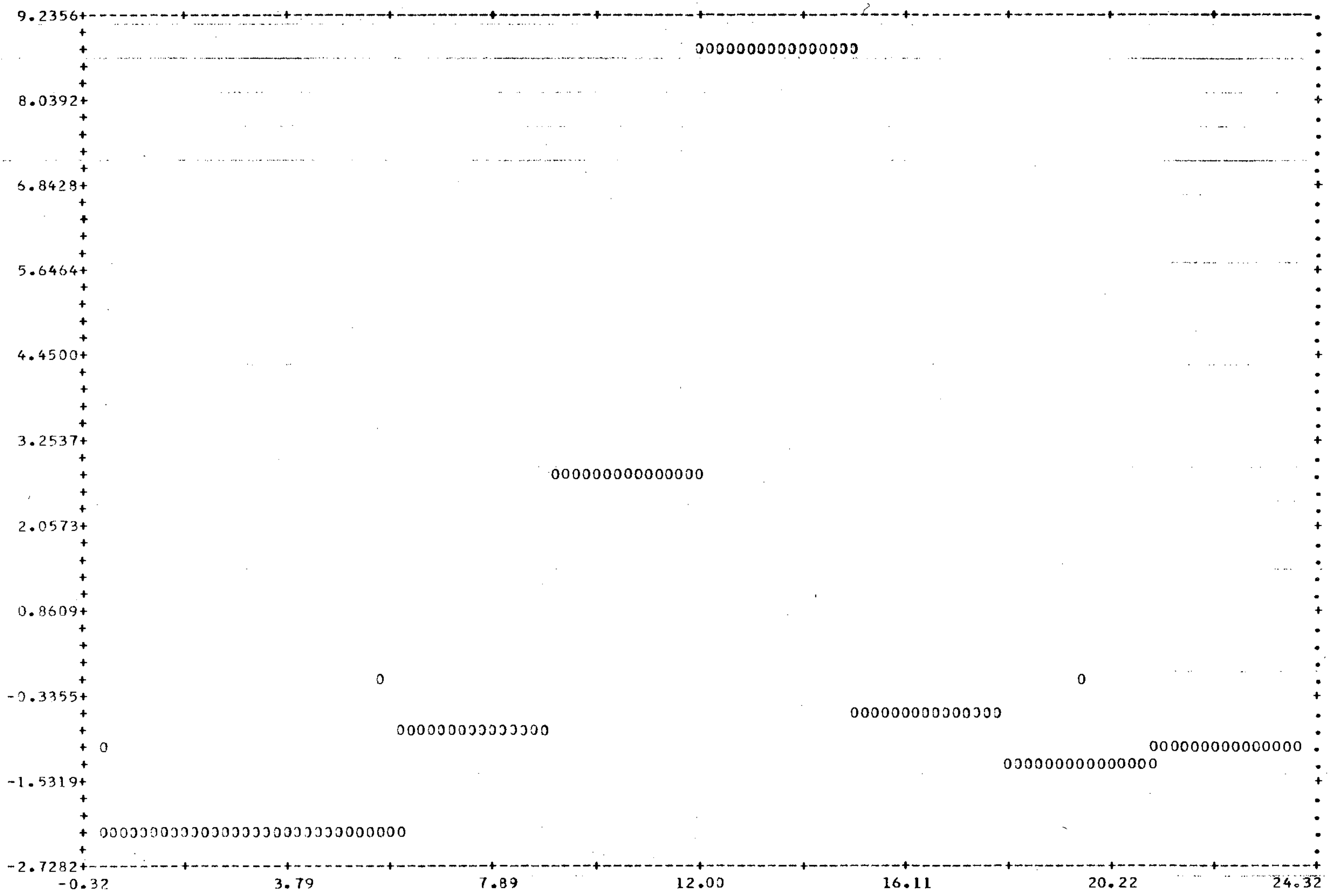

Y-AXIS = RATE OF CHANGE IN GRAMS-OF-OXYGEN/M**2/HOUR
A SHALLOW POND IN DELHI, INDIA

X-AXIS = TIME IN HOURS
STATION 1 SUBSTATION 1 DATE 6/21/59

VITA

3

Rex Lyman Eley

Candidate for the Degree of

Doctor of Philosophy

Thesis: PHYSICOCHEMICAL LIMNOLOGY AND COMMUNITY METABOLISM OF KEYSTONE RESERVOIR, OKLAHOMA

Major Field: Zoology

Biographical:

Personal Data: Born in Hope, Arkansas, 24 August 1942, the son of Glen D. and Thelma B. Eley.

Education: Graduated from Nashville High School, Nashville, Arkansas, 1961; received the Bachelor of Science degree, Southern State College, Magnolia, Arkansas, May, 1965, with a major in biology and a minor in chemistry; received the Master of Science degree, with a major in zoology, Oklahoma State University, Stillwater, Oklahoma, May, 1967; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in 1970.

Professional Experience: Student Trainee, Fisheries (GS-3) Fish Farming Experimental Station, Bureau of Sport Fisheries and Wildlife, Stuttgart, Arkansas, 1962; graduate research assistant for Oklahoma Department of Wildlife Conservation through the Oklahoma Fish and Game Council at Oklahoma State University, 1965-67; Fishery biologist (GS-5), U. S. Army Corps of Engineers through the Oklahoma Fish and Game Council at Oklahoma State University, 1967-68; Federal Water Pollution Control Administration research fellow at Oklahoma State University, 1968-69; Assistant Professor of Biology at Southern State College, Magnolia, Arkansas, 1969-1970.

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