NATIONAL WATER–QUALITY ASSESSMENT PROGRAM

Nutrient Dynamics in Five Off-Stream Reservoirs in the Lower South Platte River Basin, March–September 1995

Water-Resources Investigations Report 02–4142

U.S. Department of the Interior
U.S. Geological Survey

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By Lori A. Sprague

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02–4142

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U.S. DEPARTMENT OF THE INTERIOR
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FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multiscale approach helps to determine if certain types of water-quality issues are isolated or pervasive and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings.

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, nongovernment organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS AND WATER-QUALITY UNITS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per day (acre-ft/d)	0.5042	cubic feet per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch	2.540	centimeter (cm)
meter	3.281	foot (ft)
acre	4,047	square meter
square mile (mi^2)	2,590	square kilometer
pound (lb)	0.4536	kilogram
liter (L)	0.2642	gallon
mile (mi)	1.609	kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = 9/5\,(°C) + 32$$

The following abbreviations also are used in this report:

milligrams per liter (mg/L)
micrograms per liter (µg/L)
micrometer (µm)
microsiemens per centimeter at 25 degrees Celsius (µS/cm)
milligrams per meter squared per day ($mg/m^2/d$)

Nutrient Dynamics in Five Off-Stream Reservoirs in the Lower South Platte River Basin, March–September 1995

By Lori A. Sprague

Abstract

In 1995, the U.S. Geological Survey conducted a study to characterize nutrient concentrations in five off-stream reservoirs in the lower South Platte River Basin—Riverside, Jackson, Prewitt, North Sterling, and Julesburg. These reservoirs are critical sources of irrigation water for agricultural areas, and several also are used for fishing, boating, swimming, hunting, and camping. Data collected for this study include depth profiles of water temperature, dissolved oxygen, pH, and specific conductance; nutrient species concentrations in the water column, bottom sediment, and inflow and outflow canals; and chlorophyll-*a* concentrations in the water column. Data were collected during the irrigation season from March through September 1995 at five sites each in Riverside, Jackson, Prewitt, and Julesburg Reservoirs and at six sites in North Sterling Reservoir.

The five reservoirs studied are located in similar geographic, climatic, and land-use areas and, as a result, have a number of similarities in their internal nutrient dynamics. Nitrogen concentrations in the reservoirs were highest in March and decreased through September as a result of dilution from river inflows and biological activity. From March through June, decreases in nitrogen concentrations in the river and biological activity contributed to decreases in reservoir concentrations. From July through September, inflows from the river were cut off, and biological activity in the reservoirs led to further decreases in nitrate concentrations, which fell to near or below detectable levels. Phosphorus concentrations in the reservoirs did not show the same consistent decrease from March through September. Phosphorus likely was recycled continuously back to algae during the study period through processes such as excretion from fish, decay of aquatic plants and animals, and release of orthophosphate from bottom sediment during periods of low oxygen. With the exception of phosphorus in Jackson Reservoir, the reservoirs acted as a sink for both nitrogen and phosphorus; the percentage of the total mass (initial storage plus inflows) trapped in the reservoirs during the study period ranged from 49 to 88 percent for nitrogen and from 20 to 86 percent for phosphorus.

The nutrient loading, morphology, and operation of the five reservoirs differed, however, leading to several important differences in nutrient dynamics among the reservoirs. Mean nutrient concentrations during the study period decreased in a downstream direction from Riverside Reservoir to Julesburg Reservoir because concentrations in the source water—the South Platte River—decreased downstream as a result of increased distance from wastewater loading upstream from Kersey, Colorado, and the replacement of diverted river water with more dilute ground-water return flow. North Sterling was an exception to this decrease; the strong stratification and resulting anoxia that developed in the reservoir led to nutrient release from the bottom sediments that offset the decrease in external nutrient loading.

Variations in nutrient loading also contributed to differences in the nutrient limiting algal growth in the reservoirs, as indicated by mass nitrogen:phosphorus ratios. In Riverside and Jackson Reservoirs, nitrogen became the potential limiting nutrient by midsummer as biological activity depleted the available supply of nitrogen while the high initial phosphorus load was recycled. Prewitt, North Sterling, and Julesburg Reservoirs, with lower initial loadings of phosphorus, were phosphorus-limited throughout the study period, with additional colimitation of nitrogen as biological uptake reduced nitrogen concentrations to near or below laboratory detection limits. The percentage of the total nitrogen and phosphorus mass lost through outflow and trapped in the reservoir due to processes such as biological uptake and sedimentation varied between reservoirs. Generally, reservoirs with short residence times such as North Sterling and Julesburg lost a higher percentage of the total mass in the outflow, whereas reservoirs with longer residence times like Jackson and Prewitt trapped more of the total mass within the reservoir.

Algal biomass, as measured by chlorophyll-*a* concentrations, generally increased in all reservoirs during the study period as nutrient concentrations decreased. Mean values of Carlson's trophic-state index ranged from 59 in Riverside Reservoir to 72 in Jackson and North Sterling Reservoirs, indicating that all five reservoirs were eutrophic. The results of this study demonstrate that the practice of storing South Platte River water in off-stream reservoirs substantially decreases dissolved nitrogen concentrations during the irrigation season. Associated with the decreased nitrogen concentrations, however, is an increase in algal biomass, which could adversely affect the recreational use of the reservoirs.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) began a study of the South Platte River Basin as part of the National Water-Quality Assessment (NAWQA) Program. The goals of the NAWQA Program are to assess the quality of surface water, ground water, and aquatic ecosystems throughout the Nation and to understand the primary natural and anthropogenic factors that affect the quality of these resources. This information supports national, regional, State, and local decision making for water-quality management.

One issue of concern in the South Platte River Basin is nutrient enrichment in off-stream reservoirs. Although nutrients are necessary for plant and animal life, in excessive quantities they can accelerate the growth of aquatic plants and cause algal blooms that deprive deeper waters of the sunlight needed by aquatic plants and animals (Wetzel, 1983). The subsequent decomposition of algae and other aquatic plants consumes dissolved oxygen, which can adversely affect fish and other aquatic life. Algal blooms and excessive aquatic growth also may result in unsuitable habitat and recreation conditions.

In 1995, the USGS conducted a study to characterize nutrient concentrations in five off-stream reservoirs in the lower South Platte River Basin—Riverside, Jackson, Prewitt, North Sterling, and Julesburg—during the irrigation season from March through September. These reservoirs serve as critical sources of irrigation water for agricultural areas in the basin. Several also are used for fishing, hunting, boating, and swimming, and all are habitats for waterfowl, including bald eagles, white pelicans, and a variety of ducks and geese.

Purpose and Scope

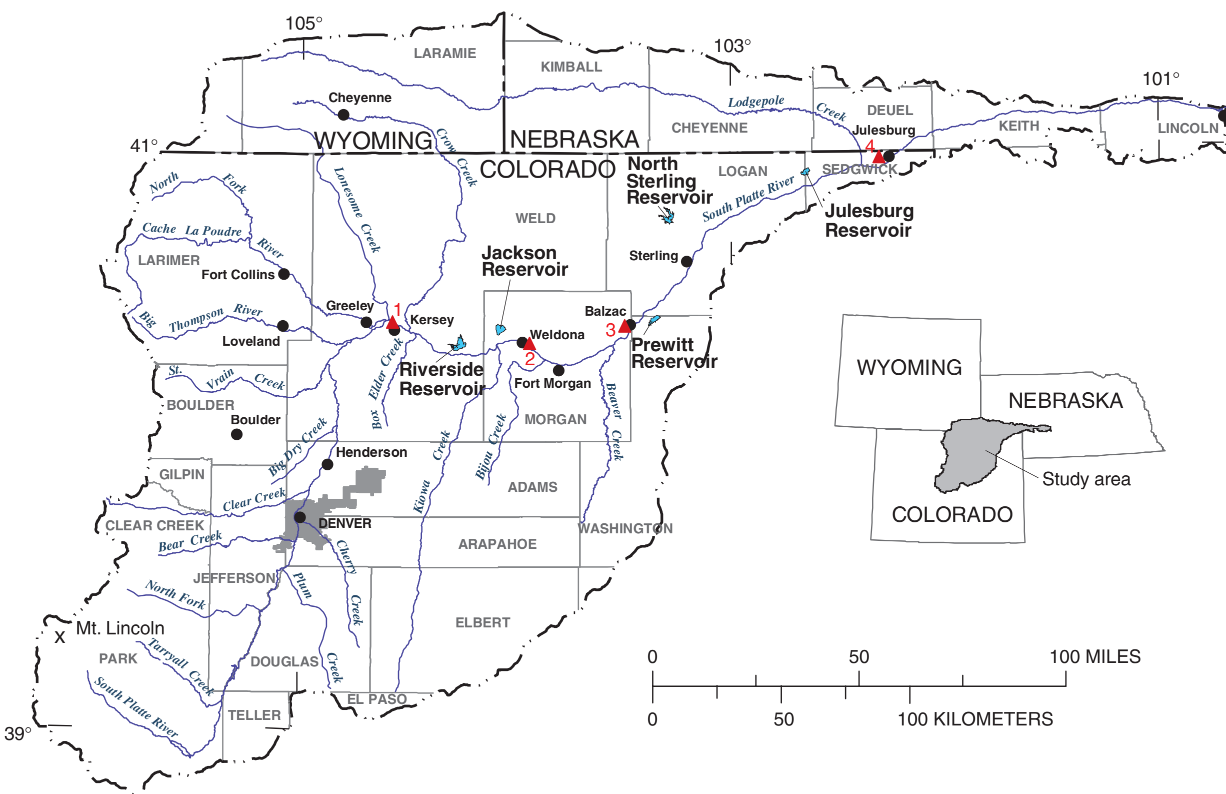
The purposes of this report are to (1) describe the spatial and temporal variation in nutrient concentrations in five off-stream reservoirs in the lower South Platte River Basin, (2) determine whether the reservoirs are a source or a sink of nutrients in irrigation-supply water, and (3) determine how the nutrient dynamics in the reservoirs differ from one another. Data collected for this study include depth profiles of water temperature, dissolved oxygen, pH, and specific conductance; nutrient species concentrations in the water column, bottom sediments, and inflow and outflow canals; and chlorophyll-*a* concentrations. These data were collected during the irrigation season from March through September 1995 at five sites each in Riverside, Jackson, Prewitt, and Julesburg Reservoirs and at six sites in North Sterling Reservoir.

Description of the South Platte River Basin

Physical Setting

The South Platte River Basin has a drainage area of about 24,300 mi² and is located in parts of three States (fig.1)—Colorado (79 percent of the basin), Nebraska (15 percent of the basin), and Wyoming (6 percent of the basin). The South Platte River originates in the Rocky Mountains of central Colorado at the Continental Divide and flows about 450 mi northeast across the Great Plains to its confluence with the North Platte River at North Platte, Nebr. Altitude in the basin ranges from 14,286 ft at Mt. Lincoln on the Continental Divide to 2,750 ft at the confluence of the South Platte and North Platte Rivers at North Platte, Nebr. (Dennehy and others, 1993).

The basin has a continental-type climate modified by topography, resulting in large temperature ranges and irregular seasonal and annual precipitation (Gaggiani and others, 1987). Mean temperatures increase from west to east and on the plains from north to south. Areas along the Continental Divide average 30 inches or more of precipitation annually, which includes snowfall in excess of 300 inches. In contrast, annual precipitation on the plains east of Denver, Colo., and in the South Park area in the southwest part of the basin, ranges from 7 to 15 inches. Most precipitation on the plains results from rainfall, which primarily occurs between April and September, while



Base from U.S. Geological Survey and U.S. Census Bureau digital data, 1974 to 1993

EXPLANATION

STREAMFLOW-GAGING AND WATER-QUALITY STATION

▲1 06754000—South Platte River near Kersey, Colorado

▲2 06758500—South Platte River near Weldona, Colorado

▲3 06759910—South Platte River near Cooper Bridge, near Balzac, Colorado

▲4 06764000—South Platte River at Julesburg, Colorado

Figure 1. Locations of study reservoirs and river water-quality sites in the South Platte River Basin.

most precipitation in the mountains results from snowfall, which primarily occurs during the winter.

Land use in the South Platte River Basin is dominated by rangeland and agriculture, at 41 percent and 37 percent, respectively (Fegeas and others, 1983). Rangeland is present across all areas of the basin except over the high mountain forests. Agricultural land is present primarily in the plains areas and Park County. Forested area is the third largest land cover, at 16 percent, and is present in a north-south band in the mountains. Urban areas cover 3 percent of the basin, primarily in the Front Range urban corridor along the base of the Rocky Mountains. The remaining land uses in the basin include barren lands, tundra, and perennial snow and ice.

Hydrology

Perennial flow in the South Platte River and its major tributaries that originate in the Rocky Mountains is derived primarily from snowmelt runoff. Smaller tributaries in the plains are ephemeral and contribute little flow to the South Platte River except during spring and summer thunderstorms. The natural hydrology of the South Platte River Basin, however, has been modified considerably by water regulation. Each year, more than 3 million acre-ft of water is removed from the river through a complex network of ditches and pipes, more than 2 million acre-ft of water is stored in reservoirs, 400,000 acre-ft of water is imported through interbasin transfers from the Colorado, Arkansas, and North Platte River Basins, and an estimated 1 million acre-ft of water is pumped by ground-water wells (Dennehy and others, 1993). The total storage capacity of the five reservoirs monitored in this study equals approximately one-fourth of the annual streamflow in the South Platte River at Kersey, Colo.

An examination of flow conditions during 1995 gives a general picture of water routing in the lower South Platte River from Kersey to Julesburg (fig. 2). Flow during January through April was low, as there was little precipitation and water was being diverted for storage in reservoirs. In May, flow increased substantially due to snowmelt runoff from the mountains. During this period, flow generally decreased in a downstream direction from Kersey to Julesburg as water was diverted all along the river for irrigation. From June through August, flow at all sites decreased

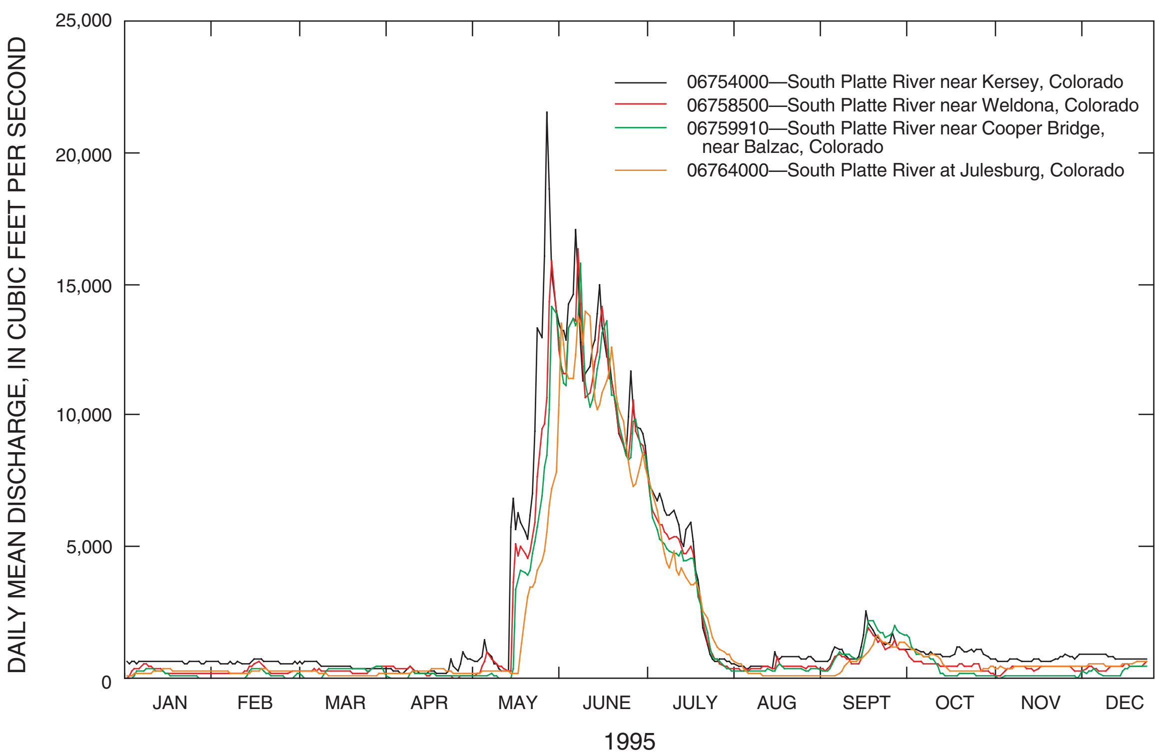


Figure 2. Daily mean discharge in the South Platte River from Kersey to Julesburg, 1995.

as snowmelt runoff ended and more water was diverted for irrigation. During the overall decrease, several small peaks occurred as runoff from seasonal storms offset water lost to diversions. The general downstream decrease in flow was still present, however. Beginning around September, irrigation diversions ended and irrigation return flows from the alluvial aquifer led to a slight increase in river flow. By mid-October, flows leveled off to near those during in January as water once again was diverted for storage in the off-stream reservoirs.

Water Quality

Nutrients are delivered to the South Platte River both from point and nonpoint sources. Point sources of nutrients can be attributed to a single location, such as a wastewater discharge pipe. Nonpoint sources of nutrients are widely distributed over an area, such as storm runoff from agricultural fields and urban areas, atmospheric deposition, and ground-water discharge to the river. About 67 percent of the total treated wastewater discharge to the South Platte River occurs upstream from Henderson, Colo., where the river flows through the Denver metropolitan area; about another 28 percent occurs between Henderson and Kersey (Litke, 1996). Because the monitoring station at Kersey is closest to the wastewater discharges, total nitrogen and total phosphorus concentrations are higher than those measured at downstream stations (fig. 3). In particular, concentrations of nitrate, ammonia, and orthophosphate, the predominant nutrient species in wastewater effluent, are high. Ammonia and orthophosphate concentrations decrease during the late spring and summer due to biologically mediated transformations to nitrate and organic phosphorus, respectively. Overall, total nitrogen and total phosphorus concentrations at Kersey are lowest during the spring and summer, when wastewater discharges are diluted by snowmelt and biological activity is greatest.

Downstream from Kersey, the influence of wastewater discharges decreases and water is derived primarily from nonpoint agricultural sources in the plains. Nutrient concentrations in the river between

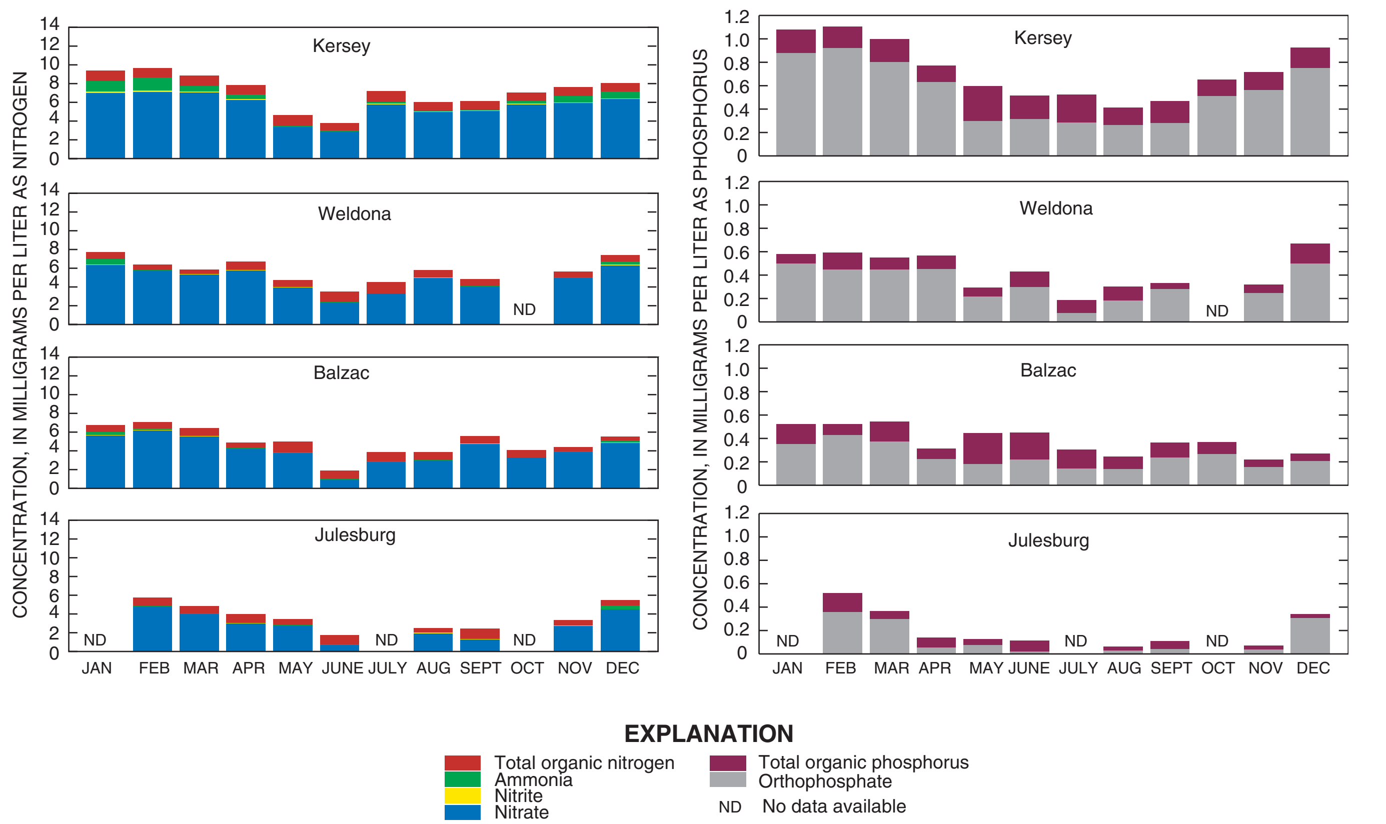


Figure 3. Monthly median concentrations of nitrogen and phosphorus in the South Platte River from Kersey to Julesburg, 1993–95.

Kersey and Julesburg decrease in a downstream direction (fig. 3), mainly because of the replacement of diverted river water with more dilute ground-water return flow. Plant uptake, incorporation into the soil, and microbial removal of a substantial portion of nitrate in returning ground water (McMahon and Böhlke, 1996) contribute to this dilution effect between diversion and return flow. Nutrient concentrations at stations downstream from Kersey also show more temporal variation than those at Kersey, largely because of seasonal agriculture diversions and ground-water return flow.

Phosphorus commonly is the nutrient that controls eutrophication in reservoirs, and the U.S. Environmental Protection Agency (USEPA) has recommended a limit of 0.1 mg/L for total phosphorus in streams and less than 0.05 mg/L where streams enter lakes and reservoirs (Horne and Goldman, 1994; U.S. Environmental Protection Agency, 1986). Total phosphorus concentrations in the South Platte River from Kersey to Julesburg commonly exceeded both limits throughout the year. The USEPA also has a set a maximum contaminant level (MCL) of 10 mg/L for nitrate in drinking water (U.S. Environmental Protection Agency, 1990). Nitrate concentrations did not exceed the standard at these sites.

A more detailed discussion of water-quality conditions in the South Platte River Basin is presented in Dennehy and others (1998) and Litke and Kimbrough (1998).

Acknowledgments

The author thanks Robert Kimbrough of the USGS for his extensive planning and field work in this study. Additional field help was provided by Dennis Smits, Patrick Edelmann, Kevin Dennehy, Peter McMahon, David Litke, Jim Collins, and Jonathan Evans. The author also acknowledges the Riverside Irrigation District for providing access to sample Riverside Reservoir.

METHODS OF DATA COLLECTION AND ANALYSIS

Water-quality data were obtained from the reservoir water column, the inflow and outflow canals, and the reservoir bottom sediment. The methods of sample collection from each area and the major computations performed on these data are described in the following paragraphs.

Data Collection

Water-quality samples were collected from the water column of each reservoir four times from March through September 1995. Five sites within Riverside, Jackson, Prewitt, and Julesburg Reservoirs and six sites within North Sterling Reservoir were selected for sampling to provide adequate coverage of the spatial variability throughout each reservoir. Immediately prior to sample collection, depth profiles of water temperature, dissolved oxygen, pH, and specific conductance were obtained at each site by using a multiparameter meter, and water transparency was measured with a black and white 20-cm-diameter Secchi disk. Generally, depth-profile measurements were taken every 0.5 ft for reservoir depths less than 10 ft, every 2 ft for reservoir depths between 10 and 20 ft, and every 5 ft for reservoir depths greater than 20 ft. Two water-quality samples then were collected at each site—a near-surface sample collected to characterize conditions in the euphotic zone (the zone of light penetration, defined as twice the Secchi-disk depth) and a near-bottom sample collected to characterize conditions at a depth where light penetration and dissolved oxygen concentrations may have been very low. All reservoir water-column samples were collected from discrete depths by using a horizontally suspended 4-L acrylic Van Dorn sampler. Near-surface samples were collected at the water surface and at intervals of about every 2 ft to twice the Secchi-disk depth and were composited in a 14-L polyethylene churn splitter. Near-bottom samples were collected at a depth of about 3 ft above the reservoir bottom. When the depth of the euphotic zone extended to less than 3 ft above the reservoir bottom, only one sample was collected.

Water-quality samples also were collected from the inflow and outflow canals of each reservoir approximately monthly from March through September to quantify nutrient loads entering and leaving the reservoir. Measurements were obtained for water temperature, dissolved oxygen, pH, specific conductance, and discharge. When sufficient water was present, depth- and width-integrated samples were collected by using the equal-width-increment method

(Edwards and Glysson, 1988); otherwise, grab samples were obtained in the centroid of flow. At times, no water was present in the canals, and no samples were collected.

Samples of the interstitial pore water in the reservoir bottom sediment were collected during the early spring and the summer to determine the potential for nutrients to move between the bottom sediment and the overlying water column. Cores were obtained with a gravity-driven coring device outfitted with acrylic core tubes at sites in the deepest parts of each reservoir, as potential for development of anaerobic conditions at the sediment/water interface was greatest at the deepest locations. Two sites were cored in each reservoir to compare and contrast results; however, only one site was cored at Riverside Reservoir because it has a sandy bottom that made retaining material in the coring device difficult. The cores, with a diameter of about 7 cm and ranging in length between 35 and 70 cm, were kept upright and transported to an onshore laboratory for processing. The top 5 cm of each core was extruded and sectioned into 1-cm samples within a nitrogen gas atmosphere to prevent oxidation, and the pore water in each sample was removed by centrifuging. The pore-water samples were filtered through 0.45-µm syringe filters.

Samples collected from the reservoir water column, bottom sediment, and inflows and outflows were treated and preserved onsite using methods described in Horowitz and others (1994) and Shelton (1994). The samples were analyzed for dissolved ammonia, dissolved nitrite, dissolved nitrite plus nitrate, total kjeldahl nitrogen, dissolved kjeldahl nitrogen, total phosphorus, dissolved phosphorus, and dissolved orthophosphate at the USGS National Water Quality Laboratory in Denver, Colo., by using colorimetric methods described in Fishman and Friedman (1989) and Fishman (1993). Samples for chlorophyll-*a* were analyzed by using a high-pressure liquid chromatography/fluorescence spectroscopy method described in Britton and Greeson (1989). Chlorophyll-*a* analysis was performed only on near-surface samples collected from the water column of three sites in each reservoir from May through September.

Instantaneous discharge in the inflow and outflow canals was measured at the time of water-quality sampling by using standard USGS stream-gaging techniques described in Rantz (1978). For each reservoir, records of daily inflow and outflow discharge estimated from stage-discharge relationships and end-of-month storage volumes estimated from area-capacity curves were obtained from the Office of the State Engineer. The estimated daily inflow and outflow discharges recorded on each sampling date were compared to the corresponding USGS discharge measurements. Because the estimated inflow discharges were higher than the measured inflow discharges for both Jackson and North Sterling Reservoirs (about 25 percent and 15 percent higher, respectively), a correction factor was applied to the estimated daily inflow records for these two reservoirs.

Data Analysis

Reservoir water quality and productivity are affected to a large extent by the amount of external and internal nutrient loading to the reservoir. External nutrient loads reflect the climate, morphology, soil type, and land use of the contributing area; internal loads reflect the amount of nutrients released from reservoir bottom sediment. To estimate the nutrient mass entering and leaving each reservoir in surface-water inflows and outflows, and to determine if the reservoirs were a source or a sink of nutrients to outflow irrigation-supply water, nutrient mass balances were calculated. In addition, the flux of nutrients from reservoir bottom sediment was calculated to estimate the internal loading to each reservoir.

Total nitrogen and total phosphorus mass balances were calculated for the period from March 1 through September 30, 1995. The general mass-balance equation is:

$$R_S = R_M + I_{MS} - O_{MS} \pm U_{MS} \qquad (1)$$

where

R_S is the final reservoir mass in storage in September, in kilograms;

R_M is the initial reservoir mass in storage in March, in kilograms;

I_{MS} is the mass in the surface-water inflow from March through September, in kilograms;

O_{MS} is the mass in the surface-water outflow from March through September, in kilograms; and

U_{MS} is the portion of the total mass that is unaccounted for from March through September, in kilograms.

The final constituent mass in reservoir storage in September was assumed to be equal to the initial mass in storage in March plus inflow mass minus outflow mass plus any inflow or minus any outflow mass that was not accounted for directly in equation 1. Inflows as reported here are those in the major inflow canals, and outflows are those in the major irrigation-supply canals. “Sources” that are unaccounted for include inflow from ephemeral streams, release from reservoir bottom sediment, runoff from surrounding land area, atmospheric deposition to the reservoir surface, and ground-water inflow; “sinks” that are unaccounted for include ground-water outflow, sedimentation, and biological uptake.

Inflow and outflow mass was calculated as the product of the concentration in a sample collected on a given date and the volume of water entering or leaving the reservoir between that date and the date of the previous sample collected. Therefore, each concentration was assumed to be representative of the period between when the sample was collected and when the previous sample had been collected. This was not always a good assumption, as inflow and outflow volumes, degrees of stratification, and levels of biological activity changed between sampling dates. In some cases, there was no inflow or outflow on a given sampling date, even though there had been substantial inflow or outflow during the period between that date and the date when the previous sample had been collected; as a result, no inflow or outflow mass for that period could be determined. Also, for Riverside and Jackson Reservoirs, there was a period of several weeks between collection of the September reservoir sample and collection of the last outflow sample that could not be accounted for appropriately in the mass balance. These uncertainties led to an unquantified, but likely fairly large, amount of error in the mass balance for each reservoir. Therefore, these mass balances should be used with caution.

The rate and direction of nutrient flux from the bottom sediment were estimated using Fick’s first law, which states that the rate of flux is directly proportional to the concentration gradient and to the porosity of the sediments (Freeze and Cherry, 1979; Kimbrough, 1999):

$$J = -\phi D_s(\delta C/\delta\chi) \qquad (2)$$

where

J is the constituent flux, in milligrams per square centimeter per day;

ϕ is the porosity of the bottom sediment;

D_S is the bulk sediment diffusion coefficient, in square centimeters per day; and

$\delta C/\delta\chi$ is the concentration gradient, in grams per liter per centimeter.

Flux estimates were not included in the mass-balance equation (1) because the small number of bottom-sediment samples collected may not adequately represent the variations in nutrient flux rates throughout the entire study period or throughout the entire reservoir bottom area.

Nutrient loading to the reservoir is an important regulator of productivity, the rate of biomass formation. The primary productivity of phytoplankton, commonly known as algae, can increase markedly with increased nutrient loading and lead to extensive algal blooms. Primary producers fix light energy with chlorophyll to convert carbon dioxide to organic matter through photosynthesis (Smith, 1990). Chlorophyll-*a* is the primary pigment in algae that produces chemical energy during photosynthesis (Horne and Goldman, 1994). Therefore, chlorophyll-*a* was used in this study as a measure of the quantity of algae present in each reservoir. Because chlorophyll-*a* concentrations can be affected by various environmental factors that do not affect algal biomass (Britton and Greeson, 1989), they should be considered as only an approximation of the true algal biomass.

Chlorophyll-*a* concentrations also were used to provide an indication of the trophic state of each reservoir, a relative classification that reflects the extent of nutrient enrichment in a water body. Higher concentrations of chlorophyll-*a* (in the range from 2.7 to 78 μg/L) are characteristic of eutrophic reservoirs with high nutrient concentrations, low light penetration, frequent algal blooms, and high densities of phytoplankton and zooplankton; whereas lower concentrations (in the range from 0.3 to 4.5 μg/L) are indicative of oligotrophic reservoirs with low nutrient concentrations, high light penetration, and low densities of phytoplankton and zooplankton (Organization for Economic Cooperation and Development, 1982). Mesotrophic reservoirs are those in transition between oligotrophic and eutrophic conditions and generally contain chlorophyll-*a* concentrations in the range from 3 to 11 μg/L. Eutrophication may result in deterioration of water quality and aquatic life in a reservoir, which in turn may negatively affect its recreational, municipal, or agricultural use.

The chlorophyll-*a* concentration ranges characteristic of the trophic states overlap somewhat; therefore, there is not a clear distinction between eutrophic, mesotrophic, and oligotrophic conditions. Water bodies with the same chlorophyll-*a* concentrations could be classified into more than one trophic state. To address this limitation, Carlson (1977) refined the trophic classification by creating a biomass-based trophic-state index (TSI). The TSI falls on a continuous scale from 0 to 100, and every major trophic division of 10 represents a doubling of algal biomass concentration. A reservoir with a TSI value less than 40 is classified as oligotrophic; a reservoir with a TSI value between 40 and 50 is classified as mesotrophic; and a reservoir with a TSI value between 50 and 100 is classified as eutrophic. Carlson's TSI was estimated using the equation:

$$TSI(Chl) = 10\left[6 - \frac{(2.04 - 0.68 lnChl)}{ln2}\right] \quad (3)$$

where

TSI(*Chl*) is the trophic-state index computed from chlorophyll-*a* concentrations;

ln is the natural logarithm function; and

Chl is the chlorophyll-*a* concentration, in micrograms per liter.

Although Carlson (1977) suggested that chlorophyll-*a* values often may provide the best indicator of trophic state, he also developed equations to compute the TSI from Secchi-disk depth and total phosphorus concentration:

$$TSI(SD) = 10\left[6 - \frac{lnSD}{ln2}\right] \quad (4)$$

and

$$TSI(TP) = 10\left[6 - \frac{ln\left(\frac{48}{TP}\right)}{ln2}\right] \quad (5)$$

where

TSI(*SD*) is the trophic-state index computed from Secchi-disk depth;

TSI(*TP*) is the trophic-state index computed from total phosphorus concentration;

ln is the natural logarithm function;

SD is the Secchi-disk depth, in meters; and

TP is the total phosphorus concentration, in micrograms per liter.

The relationship between the three TSI values serves as a check on assumptions about the interactions between various components of the reservoir ecosystem (Carlson, 1977). The three variables should transform to approximately the same TSI value; any deviation may provide additional information on nutrient dynamics and biological activity in the reservoirs.

The primary factors that control algal biomass in most reservoirs are nitrogen and phosphorus concentrations, although other factors such as light and trace-element concentrations can be important as well; the nutrient in shortest supply will limit algal biomass. The chemical needs of phytoplankton during photosynthesis (Stumm and Morgan, 1996) are characterized by the formula:

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+$$
$$(+ \text{ trace elements and light energy}) \rightleftarrows$$
$$\underbrace{C_{106}H_{263}O_{110}N_{16}P_1}_{\text{algal protoplasm}} + 138O_2$$

The exact stoichiometry of this formula may vary from one aquatic habitat to another, but the general relationship will remain the same. During photosynthesis, nitrogen and phosphorus are taken up with carbon in the ratio 106C:16N:1P (Redfield and others, 1963). Transport of carbon dioxide from the atmosphere to the water column normally is rapid and, as a result, carbon limitation typically is not observed in reservoirs (Ryding and Rast, 1989).

To determine the potential limiting nutrient in each reservoir, mass N:P ratios were calculated and compared to the reference N:P ratio. Only samples from the near surface, where light was available for photosynthesis, were used in the calculations. Also, only biologically available forms of nitrogen (dissolved nitrite plus nitrate and dissolved ammonia) and phosphorus (dissolved orthophosphate) were used in the calculations; if dissolved orthophosphate, nitrite plus nitrate, or ammonia concentrations were below the detection level, total nitrogen and total phosphorus concentrations were used instead. Because concentration values were reported in milligrams per liter, the reference mass ratio of 7.2N:1P was used in place of the corresponding atomic ratio of 16N:1P. If the ratio of N:P was greater than 7.2, phosphorus was the potential limiting nutrient; if the ratio of N:P was less than 7.2, nitrogen was the potential limiting nutrient. If the ratio was near 7.2, then both nutrients or some other factor may have been limiting. In reservoirs where concentrations of both nitrogen and phosphorus were lower than algal-growth-limiting levels (0.020 mg/L nitrogen and 0.010 mg/L phosphorus), it is likely that both nutrients were limiting, even though the ratio of the two nutrients may have suggested otherwise (Ryding and Rast, 1989).

An additional influence on nutrient dynamics and primary production in reservoirs is water residence time. Residence time is the time necessary for a volume of water in a reservoir to be replaced by inflowing water or removed by outflowing water. Nutrient retention and stratification may be limited in reservoirs with short residence times and rapid flushing. Algal productivity also may be restricted when residence times are less than 7 days because advective cell loss may exceed the phytoplankton doubling rate (Kimmel and others, 1990). Monthly residence times for each reservoir were calculated using the equation:

$$T = \frac{V}{Q} \qquad (6)$$

where

- T is the residence time, in days;
- V is the end-of-month reservoir volume, in acre-feet; and
- Q is the monthly median reservoir outflow, in acre-feet per day.

During periods of strong stratification and minimal mixing, the calculated value may not represent accurately the true residence time, as water may selectively enter into or leave from only one layer of water. Residence times in that layer would be shorter than the calculated residence times, whereas residence times in the remaining water would be longer than the calculated residence times. Additionally, an assumption of equation 6 is that the reservoirs were at steady state, where inflow and outflow rates are identical (Hornberger and others, 1998). This was not always a valid assumption; as a result, residence times presented in this report are only estimates intended for semiquantitative comparison among the reservoirs.

RIVERSIDE RESERVOIR

Riverside Reservoir is in Weld County, Colo., about 25 mi east of Greeley (fig. 1). It is owned by Riverside Irrigation District and is the only one of the five reservoirs studied that does not serve as a State recreational area. The reservoir has an estimated maximum storage capacity of 65,000 acre-ft and receives most of its surface-water inflow from Riverside Canal (fig. 4), which originates in the South Platte River. Additional surface water enters the reservoir during storms through Sanborn Draw, an ephemeral stream on the north side of the reservoir. Water is released from the reservoir through Riverside Canal and is used primarily for irrigation; other uses include ground-water augmentation and recharge. Riverside Reservoir occasionally releases water under a direct-flow decree, which requires that inflow water be put to immediate beneficial use rather than being stored in the reservoir; during these periods, inflow must equal outflow (Mae Cunning, Assistant Division Engineer, Colorado Division of Water Resources, written commun., 2001).

During the study period, reservoir storage ranged from 63,113 acre-ft in March to 12,529 acre-ft in September (table 1, fig. 5) and maximum depth ranged from about 24 ft in March to about 12 ft in September. The reservoir normally is filled during the fall and winter, reaching maximum volumes in early spring. In 1995, the reservoir reached maximum storage in March and water was released for irrigation beginning in April. The outflow generally increased from April through August as demand for irrigation water increased; maximum outflow occurred during July and August. Correspondingly, storage volumes dropped sharply during July through September. Measurable residence times in the reservoir ranged from 259 days in April to 33 days in September as outflow increased and storage decreased (table 1).

Water-quality samples were collected at five sites throughout the reservoir (fig. 4) on March 31, June 7, July 26, and September 11, 1995. Samples for chlorophyll-*a* were collected only on the last three dates from sites 1, 2, and 5. Additional water-quality samples were collected from Riverside Canal at the inflow and the outflow of the reservoir (when flowing) on May 9, June 7, July 12, August 30, and September 28, 1995. Bottom-sediment samples were collected from site 2 on April 5 and August 30, 1995.

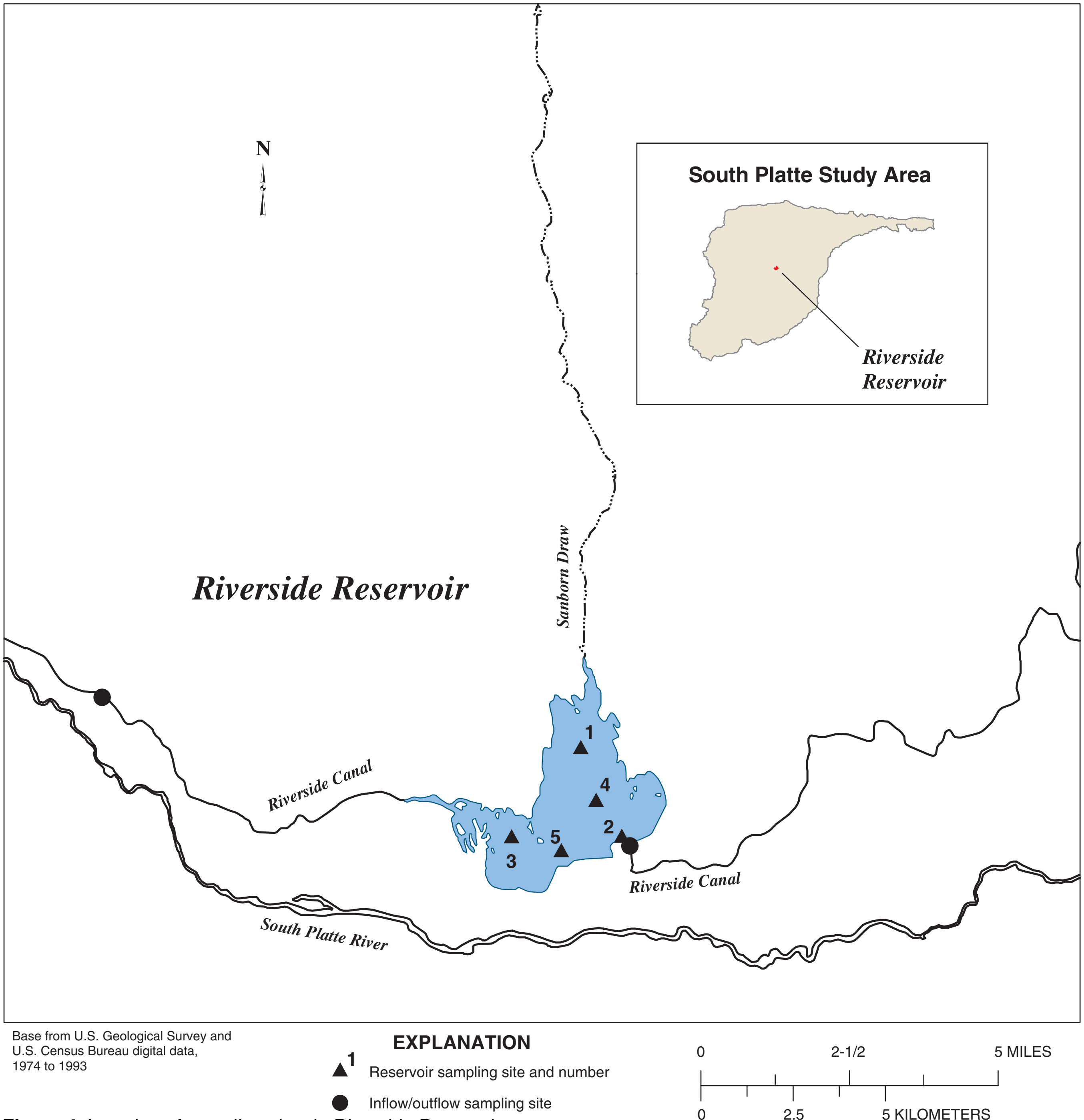


Figure 4. Location of sampling sites in Riverside Reservoir.

Water Temperature and Dissolved Oxygen

The temperature profile for March 31 indicates that the reservoir was well mixed and isothermal at all sites in early spring (fig. 6). If any stratification had existed during the winter, as is common for reservoirs in the temperate zone (Wetzel, 1983), it had been disrupted by the end of March due to loss of ice cover and warming and circulation of surface water. As spring progressed, the reservoir became moderately stratified at sites 2, 3, and 5 due to increased solar heating of surface water and the inflow of warmer water from Riverside Canal. When inflow water is warmer, and therefore less dense than the reservoir water, it will enter as overflow at the reservoir surface

Table 1. End-of-month storage, monthly median outflow, and residence time in Riverside Reservoir, March–September 1995

[acre-ft, acre-feet; acre-ft/d, acre-feet per day; --, could not be calculated]

Month	End-of-month storage (acre-ft)	Monthly median outflow (acre-ft/d)	Residence time (days)
March	63,113	0	--
April	59,300	229	259
May	63,113	190	332
June	60,479	373	162
July	49,754	768	65
August	28,600	664	43
September	12,529	379	33

(Elder and Garrison, 1965). The temperature difference between the inflow and reservoir water is reduced with distance from the inflow due to heat transfer at the air/water interface; therefore, the reservoir was only weakly stratified in June at sites 4 and 5, located farther from inflows. In July, site 3 was still weakly stratified due to its proximity to warmer inflow water, but all other sites showed minimal stratification.

Removal of a large volume of water during July resulted in a weaker temperature and density gradient between surface water and bottom water, increasing mixing and reducing the degree of stratification at sites 1, 2, 4, and 5. By September, the reservoir volume had dropped substantially, and the reservoir had become relatively shallow. Shallow water is less stable and requires less work to distribute heat uniformly with depth (Wetzel, 1983); as a result, the reservoir was well mixed and isothermal again at all sites by late summer.

The dissolved-oxygen profile for March 31 also indicates the reservoir was well mixed and that oxygen was uniformly distributed with depth at all five sites (fig. 6). Because oxygen solubility is inversely proportional to water temperature, dissolved oxygen concentrations during the study period were highest in March when temperatures were lowest. Slight supersaturation of dissolved oxygen at site 3 indicated some photosynthetic activity in this shallow area. Reduced dissolved oxygen concentrations first were measured in early June at site 3, likely as a result of biological decomposition of the organic matter contained in the inflow water and sinking algae that had been produced in the

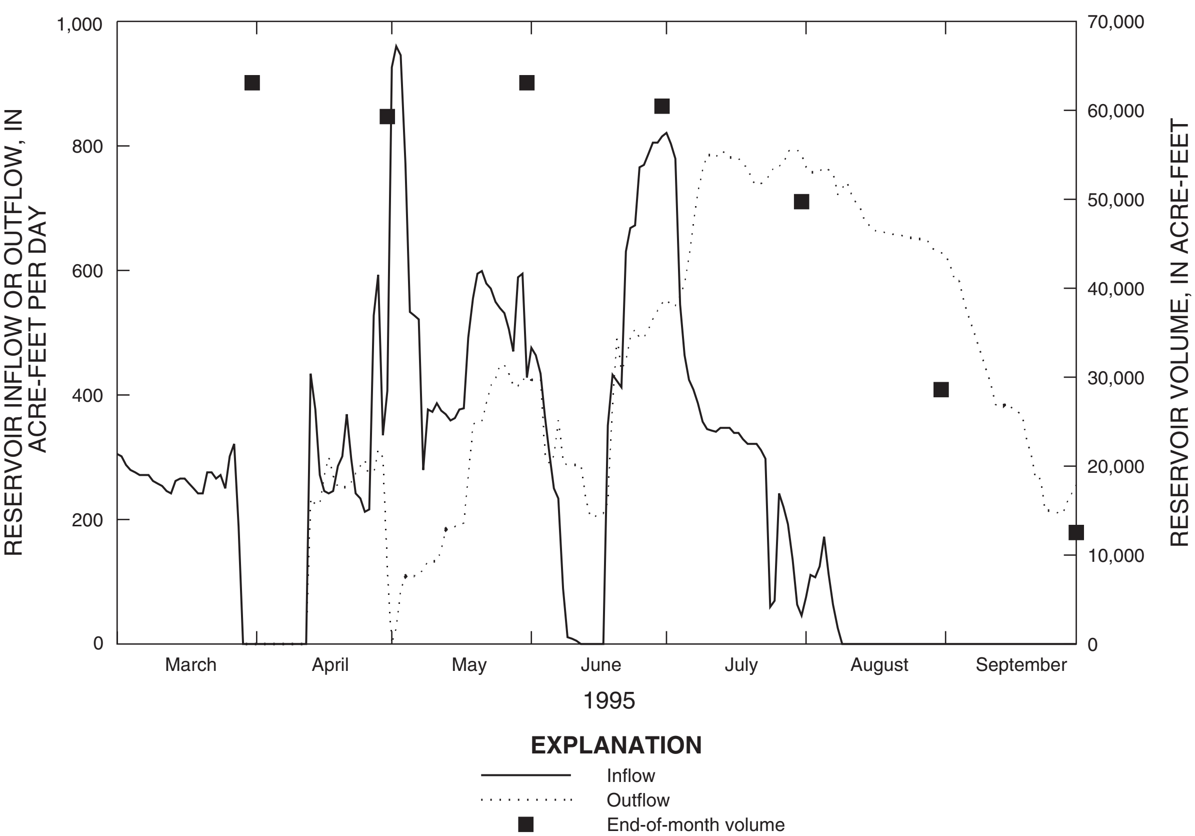


Figure 5. Inflow, outflow, and end-of-month storage volume in Riverside Reservoir, March–September 1995.

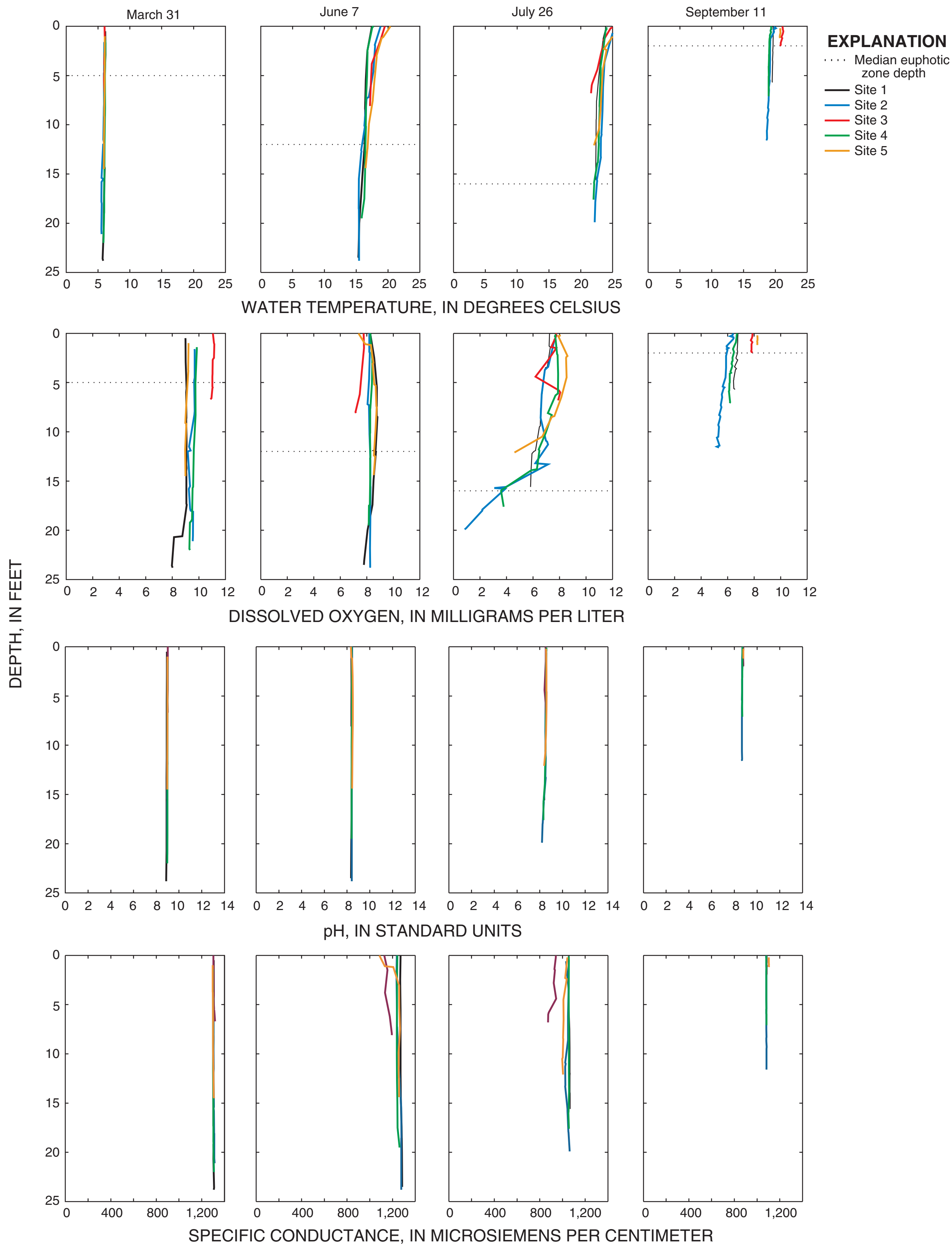


Figure 6. Depth profiles of water temperature, dissolved oxygen, pH, and specific conductance in Riverside Reservoir, March–September 1995.

euphotic zone during previous months. However, most of the organic matter in the inflow likely traveled to the main sedimentation zone near the outlet and did not settle out at site 3. This is evidenced by the zone of nearly depleted dissolved oxygen that developed in the bottom water of site 2 by July 26. The development of this anoxic zone was accelerated by large outflows during June and July, which increased mixing with warmer and less dense surface water. Mixing increased the rate of biological oxygen uptake and the delivery of organic matter and decreased oxygen solubility in the deeper water at site 2. The zone of low dissolved oxygen had spread upreservoir from site 2 to sites 4 and 5 as inflow volumes decreased during July. Even though these sites were only weakly stratified and there was only a small density gradient to impede mixing of bottom water with the oxygenated surface water, the anoxic zone in the bottom water remained. It appears that the rate of consumptive metabolism at the sediment/water interface, where settling organic matter accumulated, exceeded photosynthetic inputs in the euphotic zone during this period. By September 11, the reservoir was shallow and well mixed at all sites, and oxygen once again was uniformly distributed with depth.

pH and Specific Conductance

Most lakes and reservoirs have a pH of 6 to 9 (Horne and Goldman, 1994). In Riverside Reservoir, pH ranged seasonally between 8.0 and 9.0 (fig. 6). On all sampling dates, pH was constant from surface to bottom at all five sites. The pH value in reservoirs is primarily controlled by carbon dioxide dissolution in water, and photosynthesis and respiration are two major factors that influence the amount of carbon dioxide in water. The use of carbon dioxide during photosynthesis should increase pH in the euphotic zone, whereas the release of carbon dioxide during biological decomposition of organic matter should decrease pH at depth. However, the constant depth profiles of pH in Riverside Reservoir indicate that the system was well buffered by bicarbonate and carbonate, preventing large changes in pH, and that it likely was well mixed by wind.

The specific conductance of most lakes and reservoirs is proportional to concentrations of major ions (salinity) and can be used as a measure of inorganic water quality (Wetzel, 1983). The use of reservoir water with high specific conductance for irrigation can be detrimental to crop quality and yield, as saline water reduces the ability of plant roots to take up water (Maas, 1987). Yields of corn, the major irrigated crop in the lower South Platte River Basin, can begin to decline when irrigation water is above a specific conductance of 1,100 µS/cm, depending on local soil types, climate, and land-use practices (Aryes and Westcot, 1976). Specific conductance during the study period exceeded 1,200 µS/cm on March 31 and June 7 but had declined to near 1,000 µS/cm on July 26 and September 11 (fig. 6). The specific conductance in Riverside Reservoir was influenced largely by inflow from Riverside Canal. The highest specific-conductance values were measured on March 31 and June 7, when inflow volumes were greatest. Specific-conductance values decreased through July and September, when inflows were relatively small. The highest values in June and July were observed at sites 3 and 5, closest to the inflow. There was no spatial variation throughout the reservoir by September, as all inflow had ceased.

Nutrient Dynamics

Water-Column Concentrations

A statistical summary of nutrient concentrations at the five sites sampled in Riverside Reservoir, including euphotic and bottom samples, is provided in table 2. Median concentrations of total nitrogen during the study period ranged from 2.4 mg/L at site 1 to 4.4 mg/L at sites 2 and 4, and median concentrations of total phosphorus during the study period ranged from 0.53 mg/L at site 4 to 0.59 mg/L at site 5. A statistical analysis of nutrient concentrations using the Kruskal-Wallis test indicates that the differences in nutrient concentrations among the sites were not significant ($\alpha = 0.05$). Minimal longitudinal gradients developed, likely because the outflow volumes were substantial throughout most of the study period.

Additionally, nitrogen and phosphorus concentrations at all sites showed little difference between euphotic and near-bottom samples throughout the study period (table 3). Concentrations of nutrient species that are most readily available to biota—dissolved inorganic nitrogen, which includes ammonia, nitrate, and nitrite; and dissolved orthophosphate—were slightly lower near the surface during

Table 2. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in Riverside Reservoir, March–September 1995

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 4)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	1	7	3.4	2.0	1.9	2.4	5.2	
	2	7	3.7	2.0	1.9	4.4	5.1	
	3	4	3.3	2.2	1.9	3.1	4.5	
	4	7	3.7	2.1	1.9	4.4	5.3	
	5	5	3.9	2.2	2.4	4.3	5.8	0.9725
Dissolved ammonia	1	7	0.25	0.21	0.087	0.18	0.43	
	2	7	0.18	0.18	0.042	0.090	0.31	
	3	4	0.17	0.17	0.026	0.16	0.30	
	4	7	0.20	0.18	0.057	0.13	0.33	
	5	5	0.21	0.14	0.18	0.18	0.27	0.9488
Dissolved nitrite	1	7	0.10	0.062	0.070	0.13	0.14	
	2	7	0.10	0.062	0.070	0.13	0.14	
	3	4	0.095	0.057	0.085	0.12	0.13	
	4	7	0.10	0.062	0.070	0.13	0.14	
	5	5	0.11	0.055	0.13	0.13	0.13	0.9274
Dissolved nitrate	1	7	1.7	1.7	0.41	0.81	3.4	
	2	7	2.1	1.7	0.43	3.1	3.5	
	3	4	1.9	1.7	0.75	1.9	3.1	
	4	7	2.1	1.7	0.43	3.1	3.5	
	5	5	2.3	1.7	0.87	2.9	3.8	0.9799
Total organic nitrogen	1	7	1.3	0.38	1.0	1.2	1.5	
	2	7	1.3	0.42	0.99	1.1	1.5	
	3	4	1.1	0.51	0.85	0.90	1.1	
	4	7	1.3	0.42	0.99	1.2	1.5	
	5	5	1.3	0.44	0.99	1.0	1.7	0.6251
Total phosphorus	1	7	0.54	0.095	0.51	0.56	0.61	
	2	7	0.52	0.096	0.47	0.54	0.58	
	3	4	0.54	0.017	0.53	0.54	0.55	
	4	7	0.52	0.091	0.47	0.53	0.59	
	5	5	0.56	0.062	0.51	0.59	0.60	0.8814
Dissolved orthophosphate	1	7	0.41	0.14	0.31	0.39	0.53	
	2	7	0.39	0.12	0.31	0.37	0.49	
	3	4	0.41	0.12	0.34	0.41	0.49	
	4	7	0.40	0.12	0.31	0.38	0.49	
	5	5	0.42	0.096	0.39	0.39	0.45	0.9782
Total organic phosphorus	1	7	0.13	0.075	0.060	0.13	0.20	
	2	7	0.13	0.075	0.075	0.12	0.20	
	3	4	0.13	0.13	0.040	0.13	0.22	
	4	7	0.12	0.085	0.040	0.12	0.18	
	5	5	0.14	0.077	0.060	0.17	0.20	0.9745

Table 3. Statistical summary of nutrient concentrations in euphotic and bottom samples and results of Wilcoxon Rank-Sum test of euphotic and bottom concentration differences in Riverside Reservoir, March – September 1995

[e, euphotic; b, bottom; all concentrations are in milligrams per liter; p-value represents the probability that e and b concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Location	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	e	20	3.5	1.9	2.0	3.3	5.0	
	b	10	3.9	2.1	1.5	4.5	5.9	0.7574
Dissolved ammonia	e	20	0.22	0.18	0.026	0.23	0.34	
	b	10	0.18	0.17	0.034	0.15	0.28	0.5784
Dissolved nitrite	e	20	0.10	0.055	0.085	0.13	0.13	
	b	10	0.099	0.062	0.040	0.13	0.14	0.7246
Dissolved nitrate	e	20	1.9	1.6	0.62	1.9	3.3	
	b	10	2.2	1.8	0.22	3.1	3.7	0.7722
Total organic nitrogen	e	20	1.2	0.40	0.91	1.0	1.4	
	b	10	1.4	0.41	1.0	1.2	1.8	0.4809
Total phosphorus	e	20	0.54	0.069	0.51	0.55	0.59	
	b	10	0.52	0.098	0.44	0.55	0.59	0.7576
Dissolved orthophosphate	e	20	0.42	0.12	0.34	0.42	0.51	
	b	10	0.38	0.11	0.29	0.37	0.47	0.4150
Total organic phosphorus	e	20	0.12	0.087	0.057	0.11	0.20	
	b	10	0.14	0.070	0.075	0.14	0.20	0.6912

June and July, likely due to biological activity in the euphotic zone. Overall, however, results of a Wilcoxon Rank-Sum test indicate that there were no statistically significant differences (α=0.05) between euphotic and near-bottom nutrient concentrations during the study period. The lack of variation with depth likely is because the reservoir never developed strong stratification to limit mixing between surface water and bottom water.

Although there was little longitudinal and vertical variability in nutrient concentrations, results of a Kruskal-Wallis test indicate that there was significant (α=0.05) temporal variability in total nitrogen and total phosphorus concentrations from March through September (fig. 7). Median concentrations of total nitrogen for all data combined decreased from 6.0 mg/L in March to 1.2 mg/L in September. The decrease in total nitrogen was driven largely by a decrease in nitrate; median concentrations of nitrate dropped from 3.9 mg/L in March to below laboratory detection levels by September. During periods of substantial inflow, reservoir water quality was influenced by inflowing water from the South Platte River. From March through June, concentrations of both nitrate and total nitrogen decreased at the South Platte River at Kersey (fig. 3), the monitoring station nearest to the Riverside Canal intake. The decreases in river concentrations contributed to a corresponding decrease in reservoir concentrations during that period. However, concentrations of total nitrogen at Kersey increased in July, whereas concentrations in the reservoir continued to decrease. This suggests that biological activity also was contributing to the decline in nitrogen concentrations. Nitrate is the form of

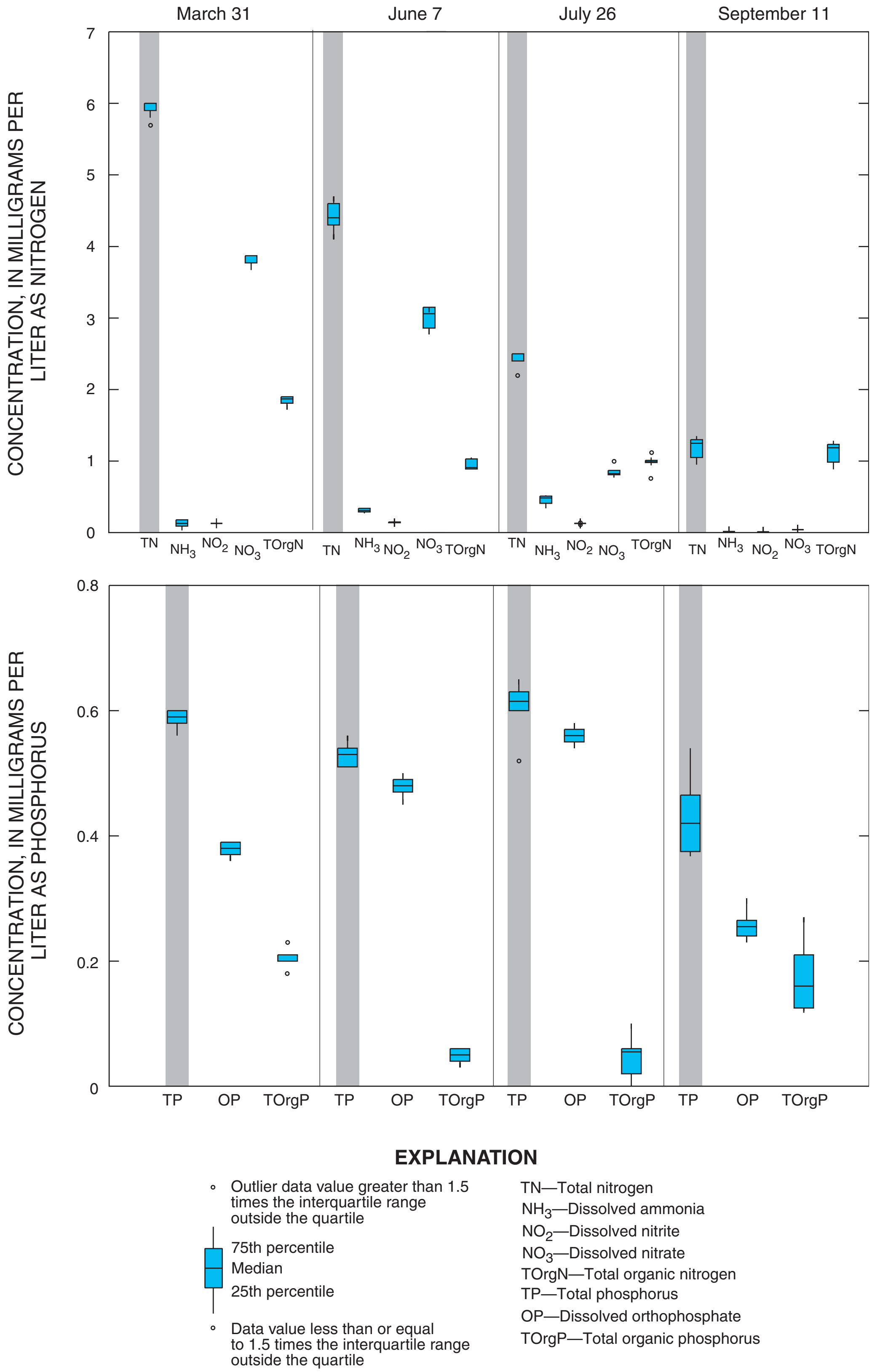


Figure 7. Nitrogen and phosphorus concentrations, euphotic and bottom samples combined in Riverside Reservoir, March–September 1995.

nitrogen most readily used by phytoplankton during growth after ammonia (Horne and Goldman, 1994), and the rate of nitrate assimilation by algae likely had exceeded the rate of nitrate inflow by July. After reservoir inflows had ended entirely in early September, continued biological activity resulted in assimilation of all remaining nitrate, and only total organic nitrogen was left in measurable quantities.

Concentrations of total phosphorus did not have the same consistent decrease during the study period as concentrations of total nitrogen. Median concentrations of total phosphorus for all data combined were lowest in September, at 0.42 mg/L, and highest in July, at 0.62 mg/L (fig. 7). The temporal pattern of total phosphorus concentrations in the reservoir did not follow that of the South Platte River at Kersey (fig. 3), indicating that internal processes had a greater effect on concentrations of phosphorus in the reservoir than inflow loading. Dissolved orthophosphate is the only biologically available form of phosphorus (Horne and Goldman, 1994), but concentrations of this phosphorus species did not decline consistently as was observed with nitrate. Instead, orthophosphate may have been recycled continuously back to algae through processes such as excretion from zooplankton and fish, decay of aquatic plants and animals, and release from bottom sediment (Wetzel, 1983).

Bottom-Sediment Flux

Estimates of nutrient flux from the bottom sediment indicate that the sediment was, at times, a potential source of nutrients to the reservoir. On April 5, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overly-ing water column at site 2 (fig. 8). The estimated flux rate for inorganic nitrogen was 21 mg/m^2/d. Concentrations of dissolved ortho-

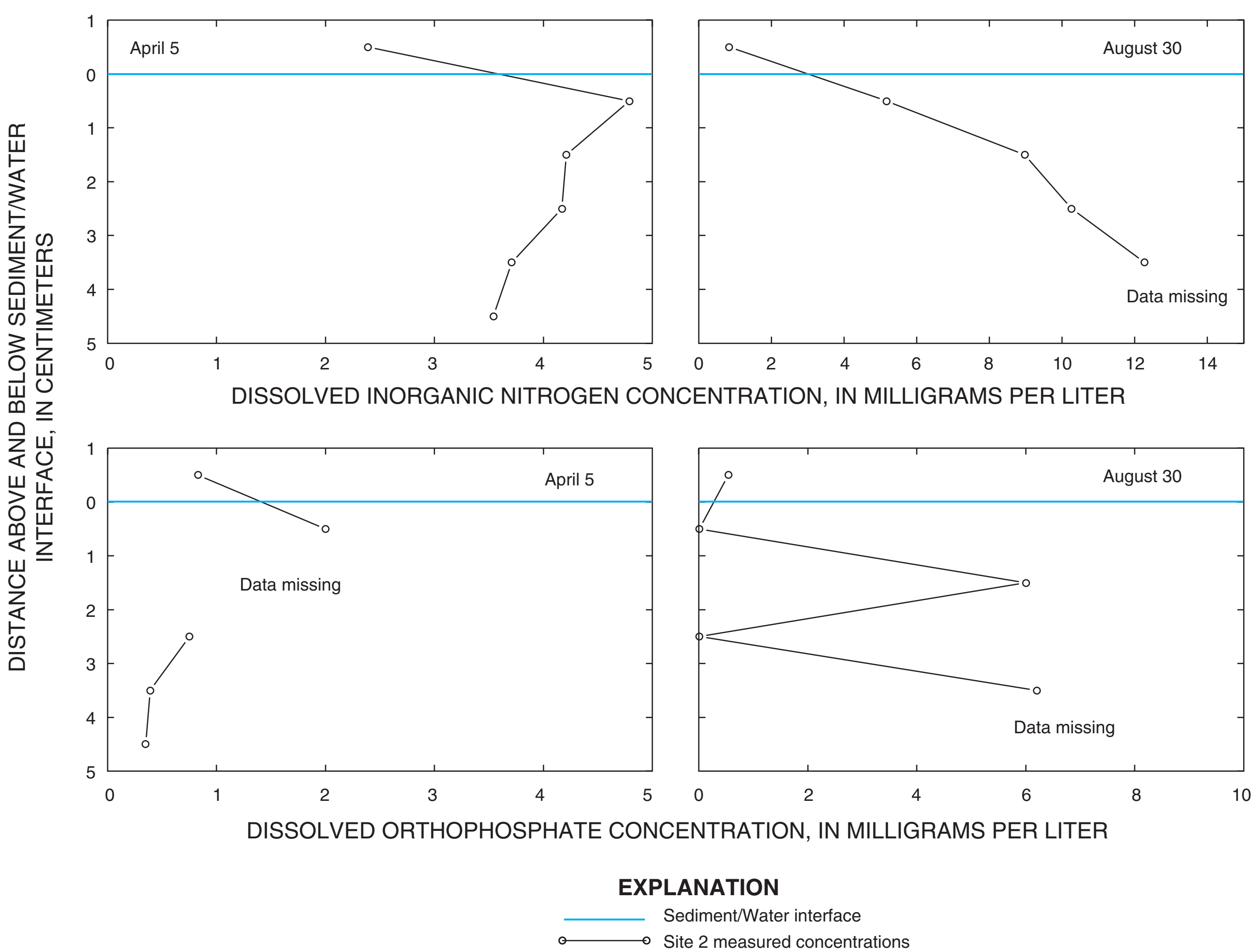


Figure 8. Concentrations of dissolved inorganic nitrogen and orthophosphate in bottom-sediment pore water and the overlying water column in Riverside Reservoir, April 5 and August 30, 1995.

phosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at site 2 on April 5. The estimated flux rate for orthophosphate was 3.8 mg/m^2/d. On August 30, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at site 2. The estimated flux rate for inorganic nitrogen was 38 mg/m^2/d. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment were lower than in the overlying water column at site 2 on August 30. The estimated flux rate for orthophosphate was –1.7 mg/m^2/d (into the sediment). Because of the limited number of samples collected, these flux estimates may not represent the spatial and temporal variations in flux throughout the reservoir and throughout the entire study period. Additionally, because bottom sediment release is redox-dependent, movement from the sediment into the overlying water column is restricted if the sediment/water interface is well oxygenated (Horne and Goldman, 1994). The near-bottom dissolved oxygen concentration at site 2 on April 5 was close to 9.5 mg/L, measured on March 31; concentrations on August 30 fell somewhere between 0.8 mg/L, measured on July 26, and 5.3 mg/L, measured on September 11. Therefore, all of these flux calculations may overestimate the movement of nutrients from bottom sediment to the water column.

Mass Balance

Mass-balance calculations for nitrogen indicate that about 68 percent of the total mass of nitrogen—the mass that had been in storage in March plus the mass that had entered in inflows through September—was trapped in the reservoir (represented by the “unaccounted for” term), while 28 percent was released through the outflow (table 4). Only 3 percent of the mass remained in the water column by September. Mass-balance calculations for phosphorus indicate that about 25 percent of the total mass of phosphorus was trapped in the reservoir, while 65 percent was released through the outflow. Only 10 percent of the mass remained in the water column by September. Much of

Table 4. Mass-balance calculations for total nitrogen and total phosphorus in Riverside Reservoir, March–September 1995

[From equation 1: Unaccounted for mass = Final storage mass – Initial storage mass – Inflow mass + Outflow mass]

Date	Total nitrogen mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 31	467,289				
April 1–May 9		73,512	0		
May 10 –June 7		27,504	52,539		
June 8–July 12		32,147	63,175		
July 13–August 30		0	54,677		
September 11					
Total	467,289	133,163	170,391	19,326	–410,735

Date	Total phosphorus mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 31	45,950				
April 1 – May 9		9,513	0		
May 10 – June 7		5,015	5,954		
June 8 – July 12		4,822	12,227		
July 13 – August 30		0	24,058		
September 11				6,416	
Total	45,950	19,351	42,240	6,416	–16,645

the nitrogen was trapped in the reservoir through biological uptake and deposition of particulate organic nitrogen onto bottom sediment. Much of the phosphorus was trapped through sedimentation of orthophosphate adsorbed to inorganic particles, deposition of particulate organic phosphorus onto bottom sediment, and biological uptake. Toward the end of the study period, the reservoir had relatively short residence times and some of the recycled phosphorus still in the water column was flushed out; much of the nitrogen, however, had already been utilized by algae and was not available to be flushed out. As a result, a greater percentage of the phosphorus mass was released through the outflow. Overall, a substantial portion of the total nutrient mass was trapped in the reservoir during the study period, and the reservoir acted as a sink for both nitrogen and phosphorus.

Algal Growth

The nutrient dynamics in the reservoir led to a change in the nutrient potentially limiting algal growth. In March, N:P values ranged from 10 to 11, indicating that phosphorus was the limiting nutrient in the early spring (table 5). In June, N:P values ranged from 6.8 to 7.3, indicating that both nutrients were potentially limiting. By July, N:P values had decreased to around 2.5, indicating that nitrogen had become the limiting nutrient. The nitrogen limitation continued into the late summer, with N:P values ranging from 1.8 to 3.3 in September. Concentrations of dissolved inorganic nitrogen species were all below the detection limit in September, giving further support that nitrogen was limiting by the end of the study period. A change in the nutrient limiting algal growth can influence the algal community structure; low N:P values typically favor the growth of nitrogen-fixing blue-green algae (Ryding and Rast, 1989).

Although chlorophyll-*a* measurements cannot provide information on the composition of the phytoplankton community, they can provide a measure of the quantity of algae present. Chlorophyll-*a* concentrations measured in the euphotic zone in June ranged from 1.4 μg/L at site 1 to 2.6 μg/L at site 2 near the outlet (table 6). By late July, chlorophyll-*a* concentrations ranged from 6.6 μg/L at site 1 to 7.8 μg/L at site 2. The higher concentrations at site 2 during the late spring and summer support the theory that much of the organic matter in the inflow traveled to a sedimentation zone near the outlet, contributing to high primary productivity in the surface water and a zone of nearly depleted dissolved oxygen in the bottom water of site 2 by late July. By September, algal biomass had increased substantially; chlorophyll-*a* concentrations ranged from 19 μg/L at site 5 to 42 μg/L at site 1. Based on mean chlorophyll-*a* concentrations, Riverside Reservoir is classified as eutrophic. Carlson's chlorophyll TSI values ranged from 43 to 49 in June, from 58 to 60 in July, and from 68 to 76 in September (table 6), indicating that the algal biomass doubled approximately three times from late spring to late summer. Chlorophyll and Secchi-disk TSI values were similar throughout the study period, though they consistently were lower than the phosphorus TSI values. The larger phosphorus TSI values support the conclusion that phosphorus was not limiting algal growth during much of the summer.

Table 5. Concentrations of biologically available nitrogen and phosphorus and N:P values for Riverside Reservoir, March–September 1995

[<, less than; DIN, dissolved inorganic nitrogen; DOP, dissolved orthophosphate; N:P, mass ratio of nitrogen to phosphorus; values of N:P calculated from total nitrogen and total phosphorus if DIN or DOP concentrations below detection limits]

Site (figure 4)	Concentration, in milligrams per liter		N:P
	DIN	DOP	
March 31			
1	4.1	0.39	11
2	4.1	0.37	11
3	4.0	0.36	11
4	4.1	0.38	10
5	4.1	0.39	11
June 7			
1	3.6	0.50	7.3
2	3.5	0.48	7.3
3	3.2	0.47	6.8
4	3.5	0.48	7.3
5	3.3	0.45	7.3
July 26			
1	1.5	0.57	2.5
2	1.4	0.55	2.6
3	1.4	0.54	2.7
4	1.5	0.58	2.5
5	1.4	0.56	2.5
September 11			
1	< 0.065	0.23	2.9
2	< 0.065	0.24	3.1
3	< 0.065	0.27	1.8
4	< 0.065	0.26	3.3
5	< 0.065	0.30	2.0

Table 6. Chlorophyll-*a* concentrations, Secchi-disk depths, total phosphorus concentrations, and associated trophic-state indices for Riverside Reservoir, March–September 1995

[µg/L, micrograms per liter; mg/L; milligrams per liter; TSI, Trophic State Index, Chl, chlorophyll-*a*; SD, Secchi disk; TP, total phosphorus]

Site (figure 4)	Chlorophyll-*a* concentration (µg/L)	TSI(Chl)	Secchi-disk depth (feet)	TSI(SD)	Total phosphorus concentration (mg/L)	TSI(TP)
			June 7			
1	1.4	43	10	44	0.56	95
2	2.6	49	6.0	51	0.51	94
5	1.8	45	6.0	51	0.51	94
			July 26			
1	6.6	58	8.0	47	0.63	97
2	7.8	60	8.0	47	0.65	98
5	7.0	59	5.0	54	0.61	97
			September 11			
1	42	76	1.0	77	0.46	93
2	33	74	1.0	77	0.43	92
5	19	68	0.50	87	0.47	93

JACKSON RESERVOIR

Jackson Reservoir is in Morgan County, Colo., about 6 mi northwest of Weldona (fig. 1). It is owned by Jackson Lake Reservoir Company and also is operated as a State Park by the Colorado Division of Parks and Outdoor Recreation. The reservoir has an estimated maximum storage capacity of 35,629 acre-ft and receives most of its surface-water inflow from Jackson Lake Inlet (fig. 9), which originates in the South Platte River. Water released from the reservoir through Jackson Lake Outlet is used primarily for irrigation; other uses include ground-water augmentation, recharge, and recreation.

During the study period, reservoir storage ranged from 26,719 acre-ft in March to 19,443 acre-ft by September (table 7, fig. 10) and maximum depth ranged from about 18 ft in March to about 15 ft in September. The reservoir normally is filled during the fall and winter, reaching maximum volumes in the early spring. In 1995, the reservoir reached maximum storage in April, and water was released for irrigation beginning in August. There were small inflows during March, April, and May and small outflows during August and September. Correspondingly, storage volumes remained fairly steady through the end of July then decreased slightly through the end of September. Measurable residence times in the reservoir ranged from 377 days in August to 560 days in September as outflow decreased slightly (table 7).

Water-quality samples were collected at five sites throughout the reservoir (fig. 9) on March 8, May 30, July 25, and September 12, 1995. Samples for chlorophyll-*a* were collected only on the last three dates from sites 2, 4, and 5. Additional water-quality samples were collected from Jackson Lake Inlet and Outlet (when flowing) on March 8, July 12, August 30, and September 28, 1995. Bottom-sediment samples were collected from sites 1 and 2 in the late winter, on February 28 and March 8, and in the summer, on August 18.

Water Temperature and Dissolved Oxygen

The temperature profile for March 8 indicates that the reservoir was well mixed at all sites in late winter; temperatures were approximately 3ºC from surface to bottom (fig. 11). In water near the temperature of maximum density (4ºC), density differences per degree of temperature change are very small (Wetzel, 1983), so very little wind energy would have been necessary to mix the water column. As spring and summer progressed, the water column remained nearly isothermal and no stratification was observed. Stratification from warmer inflow water entering as overflow did not occur, as inflow volumes during the study period were small. Additionally, because the

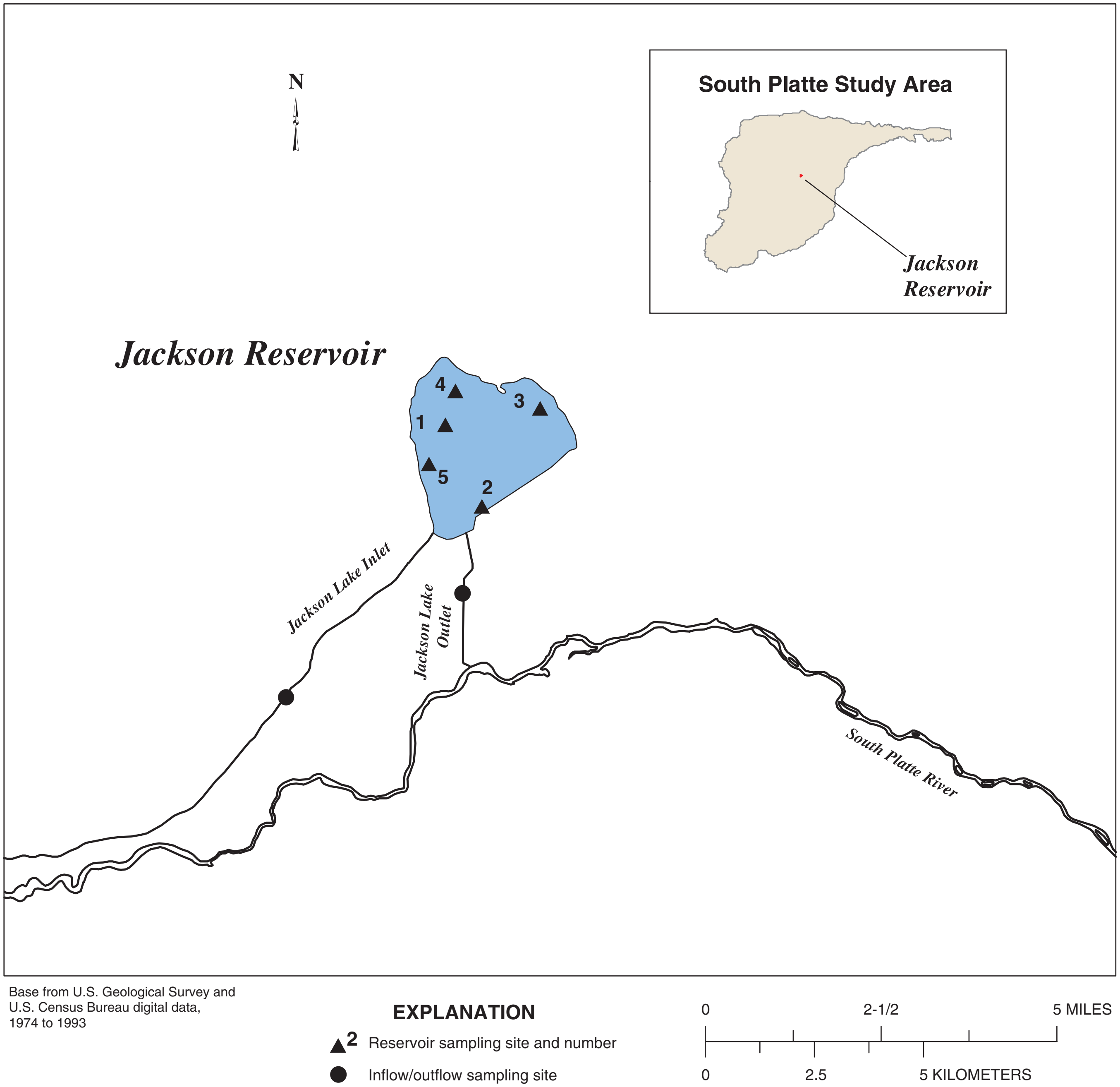


Figure 9. Location of sampling sites in Jackson Reservoir.

reservoir is relatively shallow and the surrounding terrain is flat, frequent strong winds likely helped keep the water column well mixed during the study period.

The dissolved-oxygen profile for March 8 indicates that the reservoir was well mixed and that oxygen was uniformly distributed with depth at all five sites (fig. 11). Because oxygen solubility is inversely proportional to water temperature, dissolved oxygen concentrations during the study period were highest in March when temperatures were lowest. Slight supersaturation of dissolved oxygen at site 5 indicates some photosynthetic activity in the shallowest water close to the nutrient-rich inflow water (Appendix). Reduced dissolved oxygen concentrations with depth were first observed in late July at all sites, due to biological decomposition of sinking organic matter. Though the reservoir was well mixed at this time, rates of consumptive metabolism near the bottom were high

Table 7. End-of-month storage, monthly median outflow, and residence time in Jackson Reservoir, March–September 1995

[acre-ft, acre-feet; acre-ft/d, acre-feet per day; --, could not be calculated]

Month	End-of-month storage (acre-ft)	Monthly median outflow (acre-ft/d)	Residence time (days)
March	26,719	0	--
April	27,257	0	--
May	27,257	0	--
June	26,611	0	--
July	24,893	0	--
August	20,956	56	377
September	19,443	35	560

enough to decrease bottom dissolved oxygen concentrations. Without any significant inflow during the summer to replenish nutrient loads in the reservoir, primary production likely had decreased markedly in the late summer. The concomitant decrease in decomposition reduced the dissolved oxygen gradient by September 12.

pH and Specific Conductance

In Jackson Reservoir, pH ranged seasonally between 8.0 and 9.2 (fig. 11). On all sampling dates, pH was constant from surface to bottom at all five sites. The lack of a pH difference between zones of photosynthesis and decomposition indicate that the system was well buffered by bicarbonate and carbonate, preventing large changes in pH, and that it likely was well mixed by wind. On all sampling dates, specific conductance also was constant from surface to bottom at all five sites (fig. 11). The maximum specific conductance measured during the study period was approximately 1,500 µS/cm on March 8. At this time, specific conductance was influenced primarily by inflow water; specific conductance was measured at 1,493 µS/cm in Jackson Lake Inlet that day. With little additional inflow after that date, specific conductance decreased slightly to near 1,400 µS/cm during the remainder of the study period. Because of the high salinity, use of this water for irrigation could have been detrimental to crop quality and yield (Aryes and Westcot, 1976).

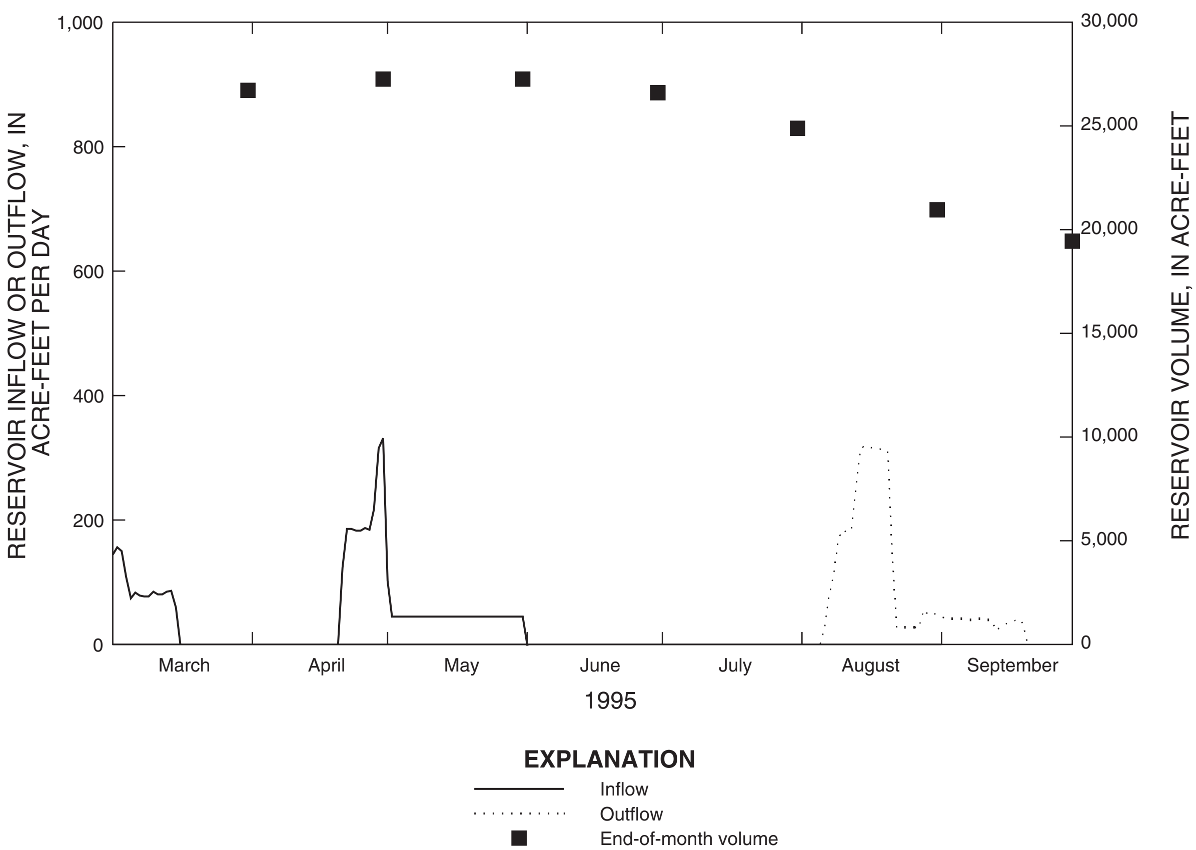


Figure 10. Inflow, outflow, and end-of-month storage volume in Jackson Reservoir, March–September 1995.

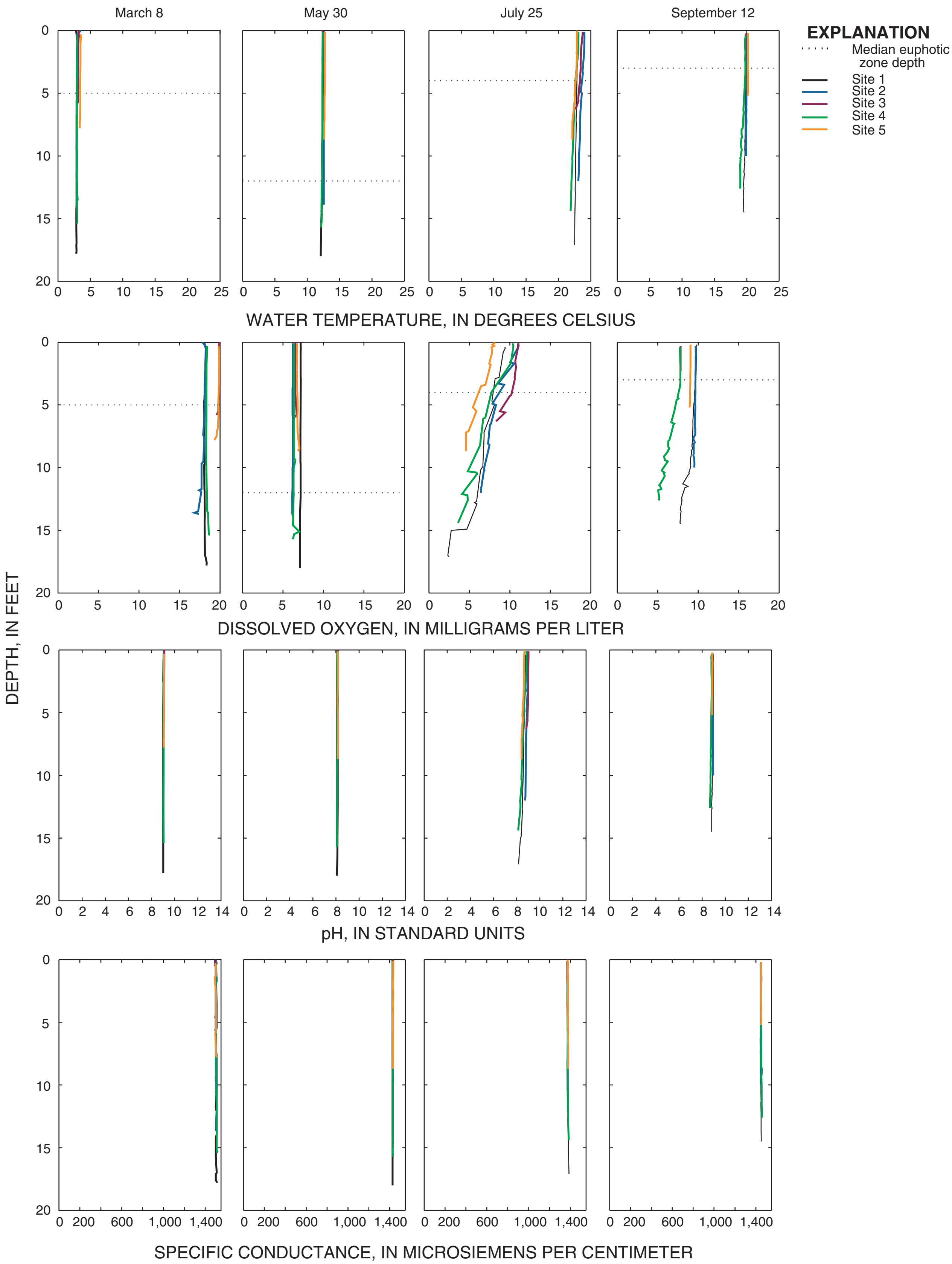


Figure 11. Depth profiles of water temperature, dissolved oxygen, pH, and specific conductance in Jackson Reservoir, March–September 1995.

Nutrient Dynamics

Water-Column Concentrations

A statistical summary of nutrient concentrations at the five sites sampled in Jackson Reservoir, including euphotic and bottom samples, is provided in table 8. Median concentrations of total nitrogen during the study period ranged from 1.9 mg/L at site 5 to 2.8 mg/L at site 4, and median concentrations of total phosphorus during the study period ranged from 0.17 mg/L at site 3 to 0.19 mg/L at sites 1, 4, and 5. A statistical analysis of nutrient concentrations using the Kruskal-Wallis test indicates that the differences in nutrient concentrations between the sites were not significant (α=0.05). Because the inflow and outflow volumes were small throughout most of the study period, there was little advective flow in the reservoir, resulting in minimal longitudinal gradients in concentration.

Samples collected near the reservoir surface and near the reservoir bottom show little difference between euphotic and bottom concentrations of nitrogen and phosphorus during most of the study period. Median concentrations of total phosphorus, orthophosphate, and dissolved inorganic nitrogen for all sites combined were slightly higher near the bottom during July, likely due to biological uptake in the euphotic zone. Overall, however, results of a Wilcoxon Rank-Sum test indicate that there were no statistically significant differences (α=0.05) between euphotic and bottom nutrient concentrations during the study period (table 9). The lack of variation with depth likely was because the reservoir never developed strong stratification to limit mixing between surface water and bottom water.

Although there was little longitudinal and vertical variability in nutrient concentrations, results of a Kruskal-Wallis test indicate that there was significant (α=0.05) temporal variability in total nitrogen and total phosphorus concentrations from March through September (fig. 12). Median concentrations of total nitrogen for all data combined decreased from 4.9 mg/L in March to 1.7 mg/L in September. The decrease in total nitrogen was driven largely by a decrease in nitrate; median concentrations of nitrate dropped from 2.9 mg/L in March to below laboratory detection levels by July. During periods of inflow, reservoir water quality was influenced slightly by inflowing water from the South Platte River. From March through May, concentrations of both nitrate and total nitrogen decreased at the South Platte River at Kersey (fig. 3), the nearest monitoring station upstream from the Jackson Lake Inlet intake. The decreases in river concentrations contributed to a decrease in reservoir concentrations during that period, though the influence of the river water likely was minor compared to internal processes, as inflow volumes were very small compared to the volume in storage. After reservoir inflows had ended entirely at the end of May, continued biological activity resulted in assimilation of all remaining nitrate by the end of July, and only total organic nitrogen was left in measurable quantities.

Concentrations of total phosphorus did not have the same consistent decrease during the study period as concentrations of total nitrogen. Median concentrations of total phosphorus for all data combined were lowest in May, at 0.11 mg/L, and highest in March and July, at 0.20 mg/L (fig. 12). The temporal pattern of total phosphorus concentrations in the reservoir appeared to follow that of the South Platte River at Kersey (fig. 3), indicating that inflow loading affected concentrations of phosphorus in the reservoir. However, as with nitrogen, the influence of the river water likely was minor compared to internal processes. After reservoir inflows had ended entirely at the end of May, biological activity continued, but phosphorus concentrations likely increased due to internal recycling.

Bottom-Sediment Flux

Estimates of nutrient flux from the bottom sediment indicate that the sediment was, at times, a potential source of nutrients to the reservoir. In late winter, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at site 1 and lower than in the overlying water column at site 2 (fig. 13). The estimated flux rates for inorganic nitrogen were 12 $mg/m^2/d$ at site 1 and –14 $mg/m^2/d$ (into the sediment) at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment were higher than in the overlying water column at sites 1 and 2 in late winter. The estimated flux rate for orthophosphate was 7.5 $mg/m^2/d$ at site 1 and 0.10 $mg/m^2/d$ at site 2. On August 18, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sedi-

Table 8. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in Jackson Reservoir, March–September 1995

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 9)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	1	8	2.8	1.4	1.8	2.3	3.3	
	2	7	2.9	1.4	1.9	2.6	3.9	
	3	4	2.7	1.6	1.8	2.2	3.1	
	4	8	3.0	1.3	2.3	2.8	3.4	
	5	6	2.4	1.5	1.5	1.9	2.6	0.8546
Dissolved ammonia	1	8	0.18	0.23	0.015	0.073	0.29	
	2	7	0.11	0.19	0.015	0.015	0.10	
	3	4	0.15	0.25	0.015	0.025	0.15	
	4	8	0.19	0.24	0.015	0.040	0.38	
	5	6	0.23	0.24	0.015	0.18	0.42	0.8895
Dissolved nitrite	1	8	0.035	0.028	0.010	0.030	0.055	
	2	7	0.030	0.026	0.010	0.010	0.050	
	3	4	0.035	0.030	0.010	0.030	0.055	
	4	8	0.035	0.028	0.010	0.030	0.055	
	5	6	0.027	0.027	0.010	0.010	0.040	0.9437
Dissolved nitrate	1	8	0.97	1.3	0.040	0.043	1.4	
	2	7	0.98	1.4	0.040	0.040	1.9	
	3	4	0.97	1.4	0.040	0.43	1.4	
	4	8	0.96	1.3	0.040	0.43	1.4	
	5	6	0.66	1.2	0.040	0.040	0.64	0.9608
Total organic nitrogen	1	8	1.6	0.33	1.3	1.7	1.8	
	2	7	1.8	0.53	1.6	1.7	1.9	
	3	4	1.5	0.44	1.1	1.5	1.9	
	4	8	1.8	0.52	1.4	1.8	1.9	
	5	6	1.5	0.49	1.3	1.5	1.7	0.7284
Total phosphorus	1	8	0.17	0.043	0.13	0.19	0.20	
	2	7	0.18	0.053	0.17	0.18	0.20	
	3	4	0.16	0.060	0.12	0.17	0.21	
	4	8	0.19	0.044	0.16	0.19	0.20	
	5	6	0.18	0.041	0.15	0.19	0.21	0.9663
Dissolved orthophosphate	1	8	0.053	0.028	0.040	0.065	0.070	
	2	7	0.053	0.031	0.030	0.070	0.075	
	3	4	0.040	0.026	0.025	0.040	0.055	
	4	8	0.053	0.030	0.040	0.055	0.073	
	5	6	0.070	0.038	0.055	0.070	0.10	0.7064
Total organic phosphorus	1	8	0.11	0.059	0.057	0.12	0.15	
	2	7	0.13	0.050	0.11	0.13	0.17	
	3	4	0.12	0.067	0.085	0.12	0.15	
	4	8	0.13	0.055	0.090	0.12	0.18	
	5	6	0.11	0.061	0.077	0.11	0.13	0.9424

Table 9. Statistical summary of nutrient concentrations in euphotic and bottom samples and results of Wilcoxon Rank-Sum test of euphotic and bottom concentration differences in Jackson Reservoir, March–September 1995

[e, euphotic; b, bottom; all concentrations are in milligrams per liter; p-value represents the probability that e and b concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Location	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	e	20	2.9	1.3	1.9	2.5	3.4	
	b	13	2.6	1.4	1.3	2.5	3.1	0.3277
Dissolved ammonia	e	20	0.17	0.23	0.015	0.025	0.39	
	b	13	0.18	0.21	0.015	0.020	0.33	1.000
Dissolved nitrite	e	20	0.035	0.027	0.010	0.030	0.055	
	b	13	0.028	0.025	0.010	0.010	0.050	0.4877
Dissolved nitrate	e	20	0.96	1.2	0.040	0.43	1.4	
	b	13	0.83	1.2	0.040	0.040	0.84	0.6405
Total organic nitrogen	e	20	1.7	0.40	1.4	1.8	1.9	
	b	13	1.6	0.55	1.3	1.6	1.8	0.3553
Total phosphorus	e	20	0.18	0.047	0.14	0.19	0.20	
	b	13	0.18	0.044	0.13	0.17	0.20	0.7947
Dissolved orthophosphate	e	20	0.049	0.028	0.025	0.050	0.070	
	b	13	0.062	0.032	0.060	0.070	0.080	0.1322
Total organic phosphorus	e	20	0.13	0.053	0.097	0.12	0.17	
	b	13	0.11	0.059	0.070	0.12	0.16	0.5414

ment were higher than in the overlying water column at sites 1 and 2. The estimated flux rates for inorganic nitrogen were 35 $mg/m^2/d$ at site 1 and 46 $mg/m^2/d$ at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at sites 1 and 2 on August 18. The estimated flux rates for orthophosphate were 9.0 $mg/m^2/d$ at site 1 and 8.3 $mg/m^2/d$ at site 2. Clearly, flux measurements on one date or at one site would not have represented the spatial and temporal variations in flux throughout the reservoir. Additionally, because bottom sediment release is redox-dependent, movement from the sediment into the overlying water column is restricted if the sediment/water interface is well oxygenated (Horne and Goldman, 1994). The bottom dissolved oxygen concentrations at site 1 and site 2 near the beginning of March were close to 18 mg/L; concentrations on August 18 fell somewhere between 3 mg/L, the minimum measured on July 25, and 9 mg/L, measured on September 12. Therefore, these flux calculations may overestimate the movement of nutrients from bottom sediment to the water column.

Mass Balance

Mass-balance calculations for nitrogen indicate that about 63 percent of the total mass of nitrogen—the mass that had been in storage in March plus the mass that had entered in inflows through September—

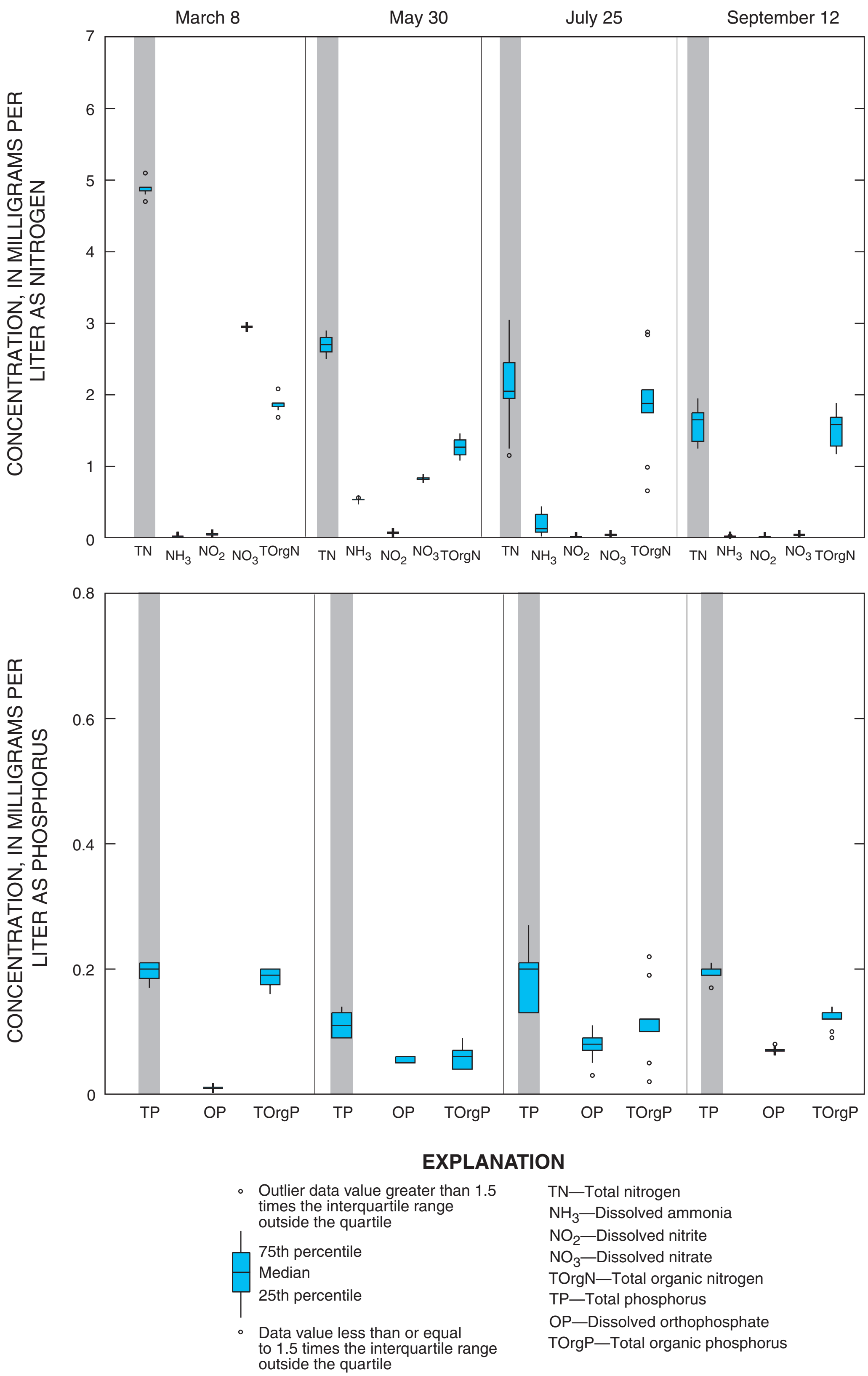


Figure 12. Nitrogen and phosphorus concentrations, euphotic and bottom samples combined in Jackson Reservoir, March–September 1995.

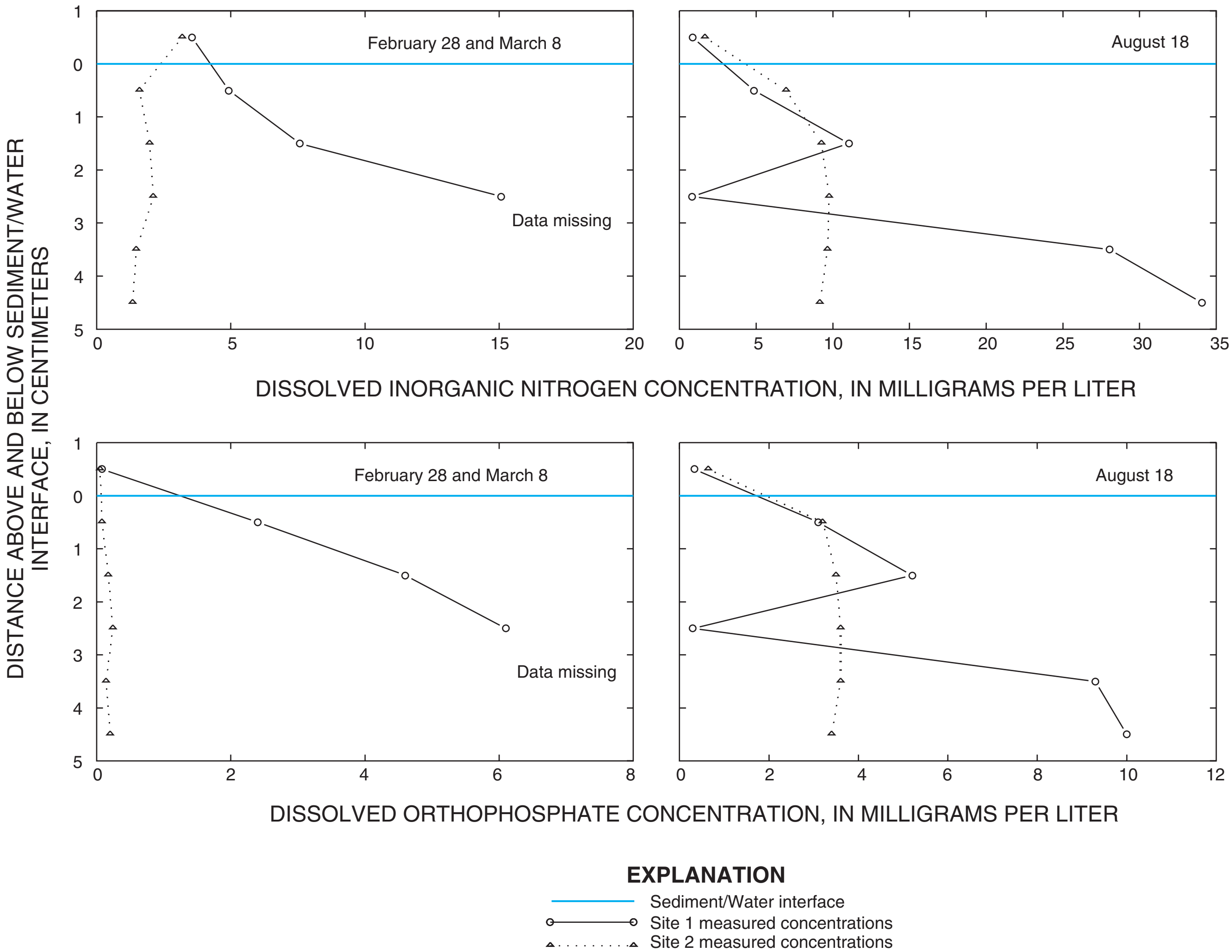


Figure 13. Concentrations of dissolved inorganic nitrogen and orthophosphate in bottom-sediment pore water and the overlying water column in Jackson Reservoir, February 28, March 8, and August 18, 1995.

was trapped in the reservoir (represented by the "unaccounted for" term), while 12 percent was released through the outflow and 25 percent remained in the water column by September (table 10). Mass-balance calculations for phosphorus indicate that about 360 kg from sources other than inflow loading was gained and retained by the reservoir; input sources could have included surface runoff and loading from ephemeral streams during storms. Approximately 36 percent of the total mass of phosphorus was released through the outflow, while 69 percent remained in the water column by September.

Much of the nitrogen likely was trapped in the reservoir through biological uptake and deposition of particulate organic nitrogen onto bottom sediment. Much of the phosphorus likely was internally recycled due to processes such as excretion from zooplankton and fish, decay of aquatic plants and animals, and release from bottom sediment (Wetzel, 1983). Because little outflow occurred, much of the recycled phosphorus was not flushed out and remained in the water column. Overall, a substantial portion of the total mass of nitrogen was trapped in the reservoir during the study period, and the reservoir acted as a sink for nitrogen. The very small gain in the total mass of phosphorus during the study period indicates that the reservoir may have acted as a minor source of phosphorus to the outflowing irrigation-supply water. It is possible also that the gain in phosphorus is attributable to error in the mass balance.

Table 10. Mass-balance calculations for total nitrogen and total phosphorus in Jackson Reservoir, March–September 1995

[From equation 1: Unaccounted for mass = Final storage mass – Initial storage mass – Inflow mass + Outflow mass]

Date	Total nitrogen mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 8	161,559				
March 9–July 12		0	10,115		
July 13–August 30		0	8,002		
August 31–September 28		0	1,428		
September 12				39,588	
Total	161,559	0	19,545	39,588	–102,426

Date	Total phosphorus mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 8	6,594				
March 9–July 12		0	850		
July 13–August 30		0	1,429		
August 31–September 28		0	114		
September 12				4,559	
Total	6,594	0	2,393	4,559	357

Algal Growth

The nutrient dynamics in the reservoir led to a change in the nutrient potentially limiting algal growth. In March, dissolved orthophosphate concentrations were below the algal-growth-limiting concentration of 0.010 mg/L, and N:P values ranged from 23 to 27, indicating that phosphorus was the limiting nutrient in the late winter (table 11). In May, phosphorus remained the nutrient limiting algal growth, as N:P values ranged from 28 to 29. By the end of July, N:P values ranged from 1.6 to 3.6, indicating that nitrogen had become the limiting nutrient. The nitrogen limitation may have ended in some portions of the reservoir by late summer, with N:P values ranging from 1.1 to 10 in September; however, these N:P values were calculated with total nitrogen and total phosphorus and may overestimate the concentrations of biologically available nitrogen and phosphorus. Concentrations of dissolved inorganic nitrogen species were all below the detection limit in September, suggesting that nitrogen was limiting at the end of the study period. The nitrogen limitation may have promoted the growth of nitrogen-fixing blue-green algae during the summer.

Although chlorophyll-*a* measurements cannot provide information on the composition of the phytoplankton community, they can provide a measure of the quantity of algae present. Chlorophyll-*a* concentrations measured in the euphotic zone in May ranged from 2.4 µg/L at site 5 to 4.1 µg/L at site 4 (table 12). By late July, chlorophyll-*a* concentrations ranged from 53 µg/L at site 5 to 150 µg/L at sites 2 and 4. Concentrations reached relatively high levels during the summer because the residence time was high and there was no advective outflow to cause phytoplankton washout. By September, algal growth had decreased; chlorophyll-*a* concentrations ranged from 50 µg/L at site 5 to 84 µg/L at site 4. Without any significant inflow during the summer to replenish nutrient loads in the reservoir, algal populations could not sustain growth. Additionally, it is possible that algal growth was restricted by zooplankton grazing or light limitation due to self-shading (Wetzel, 1983). Based on mean chlorophyll-*a* concentrations, Jackson Reser-

Table 11. Concentrations of biologically available nitrogen and phosphorus and N:P values for Jackson Reservoir, March–September 1995

[<, less than; DIN, dissolved inorganic nitrogen; DOP, dissolved orthophosphate; N:P, mass ratio of nitrogen to phosphorus; values of N:P calculated from total nitrogen and total phosphorus if DIN or DOP concentrations below detection limits]

Site (figure 9)	Concentration, in milligrams per liter		N:P
	DIN	DOP	
	March 8		
1	3.0	< 0.010	25
2	3.0	< 0.010	27
3	3.0	< 0.010	23
4	3.0	< 0.010	26
5	3.0	< 0.010	24
	May 30		
1	1.4	0.050	29
2	1.4	0.050	29
3	1.4	0.050	28
4	1.4	0.050	29
5	1.4	0.050	29
	July 25		
1	0.18	0.070	2.6
2	0.13	0.080	1.6
3	0.070	0.030	2.3
4	0.11	0.050	2.2
5	0.40	0.11	3.6
	September 12		
1	< 0.065	0.070	9.2
2	< 0.065	0.070	8.3
3	0.080	0.070	1.1
4	< 0.065	0.070	10
5	< 0.065	0.070	8.8

voir is classified as eutrophic. Carlson's chlorophyll TSI values ranged from 48 to 53 in May, from 79 to 89 in July, and from 78 to 83 in September (table 12), indicating that the algal biomass doubled approximately four times during the spring and summer. In July and September, Secchi-disk TSI values were lower than the chlorophyll and phosphorus TSI values, further evidence that the reservoir may have been light-limited during this period.

PREWITT RESERVOIR

Prewitt Reservoir is in Washington County, Colo., on the border with Logan County, about 5 mi east of Balzac (fig. 1). It is owned by Logan Irrigation District and also is operated as a State Wildlife Area by the Colorado Division of Wildlife. The reservoir has an estimated maximum storage capacity of 28,840 acre-ft and receives most of its surface-water inflow from Prewitt Inlet Canal and the agriculture drain Lower Platte and Beaver Ditch (fig. 14), which originate in the South Platte River. Water released from the reservoir through Prewitt Outlet Canal is used primarily for irrigation; other uses include ground-water augmentation, recharge, and recreation.

During the study period, reservoir storage varied from 24,976 acre-ft in March to 28,600 acre-ft in May and June, and to 20,174 acre-ft in September (table 13, fig. 15); maximum depth varied from about 17 ft in March to about 22 ft in June and to about 16 ft in September. The reservoir normally is filled during the

Table 12. Chlorophyll-*a* concentrations, Secchi-disk depths, total phosphorus concentrations, and associated trophic-state indices for Jackson Reservoir, March–September 1995

[µg/L, micrograms per liter; mg/L; milligrams per liter; TSI, Trophic State Index, Chl, chlorophyll-*a*; SD, Secchi disk; TP, total phosphorus]

Site (figure 9)	Chlorophyll-*a* concentration (µg/L)	TSI(Chl)	Secchi-disk depth (feet)	TSI(SD)	Total phosphorus concentration (mg/L)	TSI(TP)
			May 30			
2	2.5	49	6.5	50	0.09	69
4	4.1	53	6.0	51	0.14	75
5	2.4	48	4.5	55	0.12	73
			July 25			
2	150	89	2.0	67	0.20	81
4	150	89	2.0	67	0.27	85
5	53	79	2.0	67	0.21	81
			September 12			
2	72	82	1.5	71	0.20	81
4	84	83	2.0	67	0.19	80
5	50	78	1.0	77	0.20	81

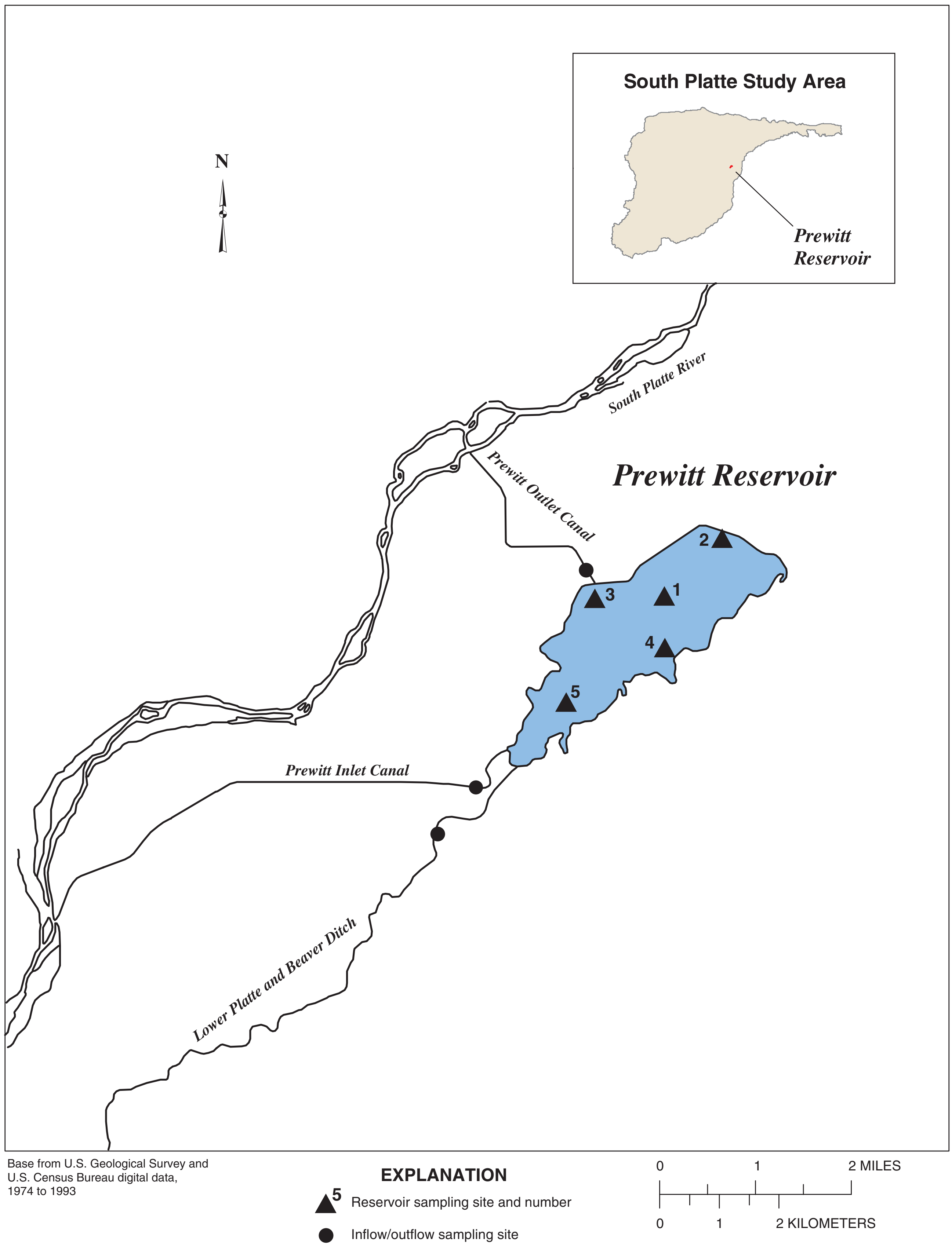


Figure 14. Location of sampling sites in Prewitt Reservoir.

Table 13. End-of-month storage, monthly median outflow, and residence time in Prewitt Reservoir, March–September 1995

[acre-ft, acre-feet; acre-ft/d, acre-feet per day; --, could not be calculated]

Month	End-of-month storage (acre-ft)	Monthly median outflow (acre-ft/d)	Residence time (days)
March	24,976	0	--
April	26,766	0	--
May	28,600	0	--
June	28,600	30	953
July	27,675	0	--
August	22,830	30	761
September	20,174	0	--

fall and winter, reaching maximum volumes in the spring. In 1995, the reservoir reached maximum storage in May and water was released for irrigation beginning in June. Outflow volumes were small relative to inflow volumes, and outflow fluctuated from June through September with demand for irrigation water. Correspondingly, storage volumes dropped only about 30 percent from June through September. Measurable residence times in the reservoir ranged from 953 days in June to 761 days in August as storage decreased (table 13).

Water-quality samples were collected at five sites throughout the reservoir (fig. 14) on March 9, June 6, August 1, and September 13, 1995. Samples for chlorophyll-*a* were collected only on the last three dates from sites 1, 2, and 4. Additional water-quality samples were collected from Prewitt Inlet Canal, Lower Platte and Beaver Ditch, and the Prewitt Outlet Canal (when flowing) on March 9, May 10, June 6, July 11, August 17, and September 13, 1995. Bottom-sediment samples were collected from sites 1 and 2 on March 9 and August 17.

Water Temperature and Dissolved Oxygen

The temperature profile for March 9 indicates that the reservoir was well mixed at all sites in late winter; temperatures were approximately 2–3°C from surface to bottom (fig. 16). The reservoir was closer to

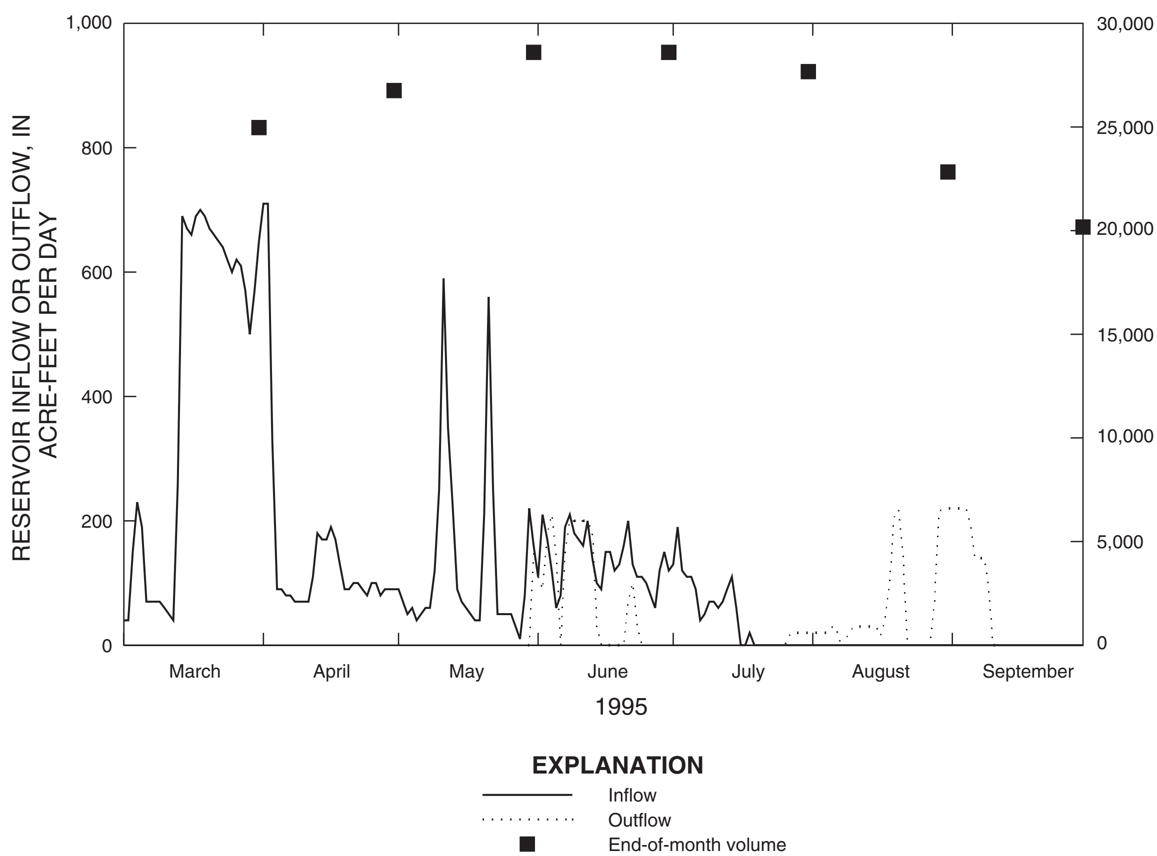


Figure 15. Inflow, outflow, and end-of-month storage volume in Prewitt Reservoir, March–September 1995.

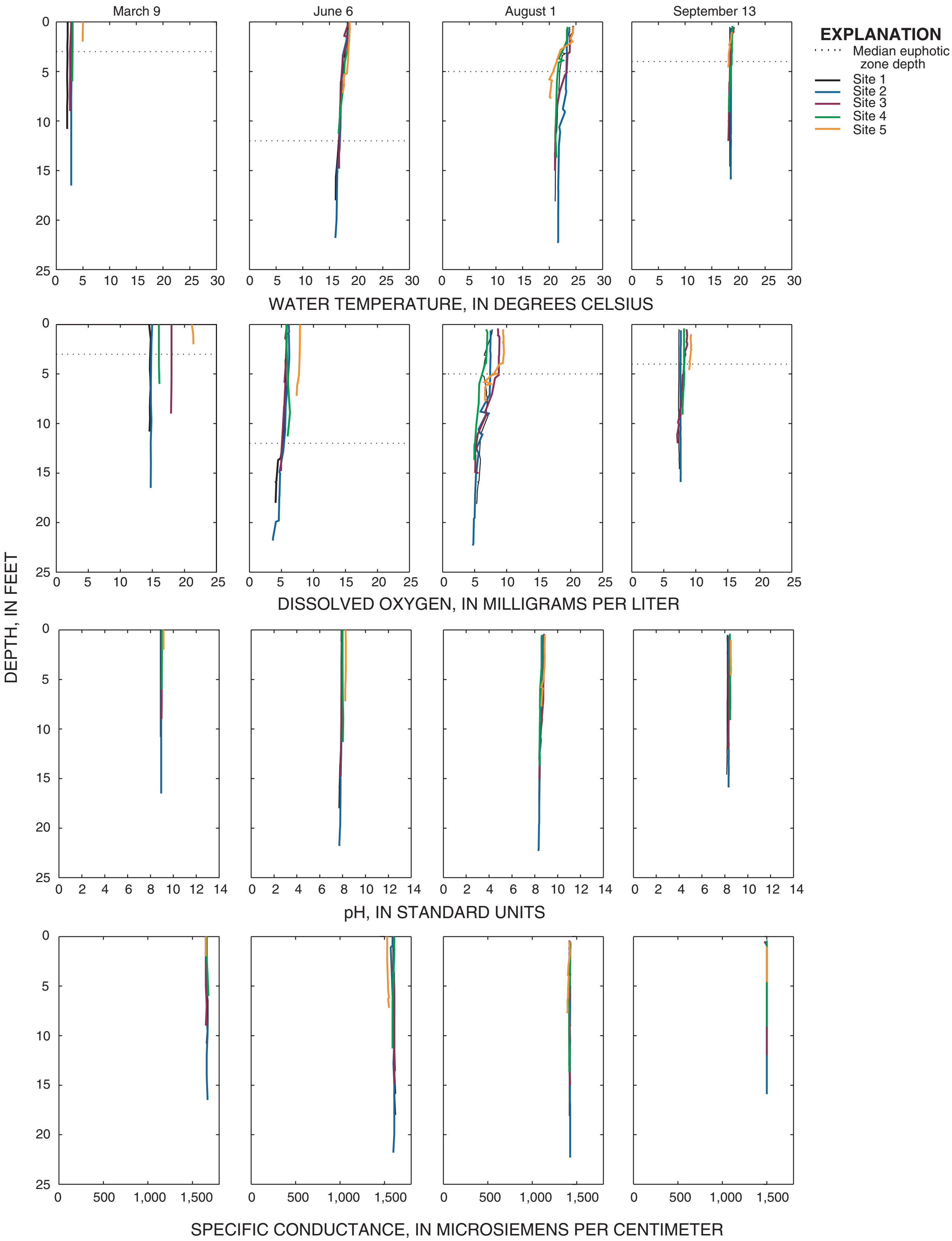


Figure 16. Depth profiles of water temperature, dissolved oxygen, pH, and specific conductance in Prewitt Reservoir, March–September 1995.

5ºC at site 5, where it was shallowest and therefore warmed more quickly. At these temperatures, very little wind energy would have been necessary to mix the water column (Wetzel, 1983). As spring progressed, all sites became weakly stratified due to increased solar heating of surface water and the inflow of warmer water from Prewitt Inlet Canal and Lower Platte and Beaver Ditch as overflow at the reservoir surface. By the beginning of August, the degree of stratification had increased slightly at all sites. Little inflow or outflow occurred during this period to disrupt the stratification. By September, the reservoir volume had dropped, evaporative heat losses had increased, and water temperatures had decreased. The shallow water was less stable, and all sites were well mixed and isothermal by late summer.

On March 9, the reservoir was well mixed and oxygen was uniformly distributed with depth at all five sites (fig. 16). Because oxygen solubility is inversely proportional to water temperature, dissolved oxygen concentrations during the study period were highest in March when temperatures were lowest. Supersaturation of dissolved oxygen at sites 3, 4, and 5 indicates some photosynthetic activity in close proximity to the nutrient-rich inflow water (Appendix). Reduced dissolved oxygen concentrations were measured in early June and August at all sites, likely due to biological decomposition of sinking organic matter. By September 13, all sites were shallower and well mixed, and oxygen once again was uniformly distributed with depth.

pH and Specific Conductance

In Prewitt Reservoir, pH ranged seasonally between 7.7 and 9.1 (fig. 16). On all sampling dates, pH was constant from surface to bottom at all five sites. The lack of a pH difference between zones of photosynthesis and decomposition indicates that the system was well buffered by bicarbonate and carbonate, preventing large changes in pH, and that it likely was well mixed by wind. On all sampling dates, specific conductance also was constant from surface to bottom at all five sites (fig. 16). The maximum specific conductance measured during the study period was approximately 1,680 µS/cm on March 9. At this time, specific conductance was influenced primarily by inflow water; specific conductance was measured at 1,960 µS/cm in Prewitt Inlet Canal that day. With smaller inflow volumes after that date, specific conductance decreased slightly to near 1,500 µS/cm during the remainder of the study period. Because of the high salinity, use of this water for irrigation could have been detrimental to crop quality and yield (Aryes and Westcot, 1976).

Nutrient Dynamics

Water-Column Concentrations

A statistical summary of nutrient concentrations at the five sites sampled in Prewitt Reservoir, including both euphotic and bottom samples, is provided in table 14. Median concentrations of total nitrogen during the study period ranged from 1.1 mg/L at site 2 to 1.6 mg/L at site 5, and median concentrations of total phosphorus during the study period ranged from 0.050 mg/L at site 2 to 0.080 mg/L at sites 1, 3, 4, and 5. A statistical analysis of nutrient concentrations using the Kruskal-Wallis test indicates that the differences in nutrient concentrations between the sites were not significant (α=0.05). Because the inflow and outflow volumes were small throughout most of the study period, there was little advective flow in the reservoir, resulting in minimal longitudinal gradients in concentration.

Samples collected near the reservoir surface and near the reservoir bottom show little difference between euphotic and bottom concentrations of nitrogen and phosphorus during most of the study period. Results of a Wilcoxon Rank-Sum test indicate that there were no statistically significant differences (α=0.05) between euphotic and bottom nutrient concentrations during the study period (table 15). The lack of variation with depth likely was because the reservoir never developed strong stratification to limit mixing between surface water and bottom water.

Although there was little longitudinal and vertical variability in nutrient concentrations, results of a Kruskal-Wallis test indicate that there was significant (α=0.05) temporal variability in total nitrogen and total phosphorus concentrations from March through September (fig. 17). Median concentrations of total nitrogen for all data combined decreased from 3.9 mg/L in March to 1.3 mg/L in September. The decrease in total nitrogen was driven largely by a decrease in nitrate; median concentrations of nitrate dropped from 1.6 mg/L in March to below laboratory

Table 14. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in Prewitt Reservoir, March–September 1995

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 14)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	1	7	2.0	1.3	1.2	1.3	2.8	
	2	7	1.9	1.4	1.0	1.1	2.8	
	3	7	2.0	1.3	1.2	1.3	2.9	
	4	6	1.8	1.0	1.2	1.5	1.8	
	5	4	2.0	1.4	1.2	1.6	2.3	0.9550
Dissolved ammonia	1	7	0.11	0.19	0.015	0.015	0.080	
	2	7	0.11	0.18	0.015	0.015	0.095	
	3	7	0.093	0.19	0.015	0.015	0.035	
	4	6	0.11	0.18	0.015	0.043	0.070	
	5	4	0.10	0.18	0.015	0.015	0.10	0.9970
Dissolved nitrite	1	7	0.016	0.015	0.010	0.010	0.010	
	2	7	0.016	0.015	0.010	0.010	0.010	
	3	7	0.016	0.015	0.010	0.010	0.010	
	4	6	0.015	0.012	0.010	0.010	0.010	
	5	4	0.013	0.017	0.010	0.010	0.017	0.9998
Dissolved nitrate	1	7	0.57	0.74	0.075	0.11	1.0	
	2	7	0.59	0.76	0.075	0.12	1.1	
	3	7	0.56	0.72	0.070	0.11	1.0	
	4	6	0.40	0.65	0.57	0.11	0.35	
	5	4	0.51	0.67	0.085	0.27	0.69	0.9816
Total organic nitrogen	1	7	1.3	0.60	0.89	1.2	1.6	
	2	7	1.2	0.66	0.81	0.89	1.5	
	3	7	1.4	0.61	0.93	1.2	1.7	
	4	6	1.2	0.46	0.92	1.2	1.4	
	5	4	1.3	0.83	0.84	1.1	1.6	0.8911
Total phosphorus	1	7	0.079	0.040	0.055	0.080	0.11	
	2	7	0.066	0.044	0.040	0.050	0.095	
	3	7	0.076	0.036	0.050	0.080	0.10	
	4	6	0.072	0.031	0.047	0.080	0.090	
	5	4	0.083	0.046	0.060	0.080	0.10	0.9653
Dissolved orthophosphate	1	7	0.013	0.0076	0.010	0.010	0.010	
	2	7	0.013	0.0076	0.010	0.010	0.010	
	3	7	0.013	0.0076	0.010	0.010	0.010	
	4	6	0.013	0.0082	0.010	0.010	0.010	
	5	4	0.015	0.010	0.010	0.010	0.015	0.9999
Total organic phosphorus	1	7	0.066	0.041	0.035	0.070	0.095	
	2	7	0.053	0.047	0.020	0.040	0.085	
	3	7	0.063	0.038	0.030	0.070	0.090	
	4	6	0.058	0.033	0.033	0.060	0.080	
	5	4	0.067	0.049	0.035	0.060	0.093	0.9488

Table 15. Statistical summary of nutrient concentrations in euphotic and bottom samples and results of Wilcoxon Rank-Sum test of euphotic and bottom concentration differences in Prewitt Reservoir, March–September 1995

[e, euphotic; b, bottom; all concentrations are in milligrams per liter; p-value represents the probability that e and b concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Location	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	e	20	2.0	1.2	1.1	1.6	2.3	
	b	11	1.9	1.3	1.1	1.3	2.6	0.6045
Dissolved ammonia	e	20	0.14	0.20	0.015	0.015	0.15	
	b	11	0.040	0.038	0.015	0.015	0.060	0.4750
Dissolved nitrite	e	20	0.019	0.017	0.010	0.010	0.017	
	b	11	0.010	0.001	0.010	0.010	0.010	0.0811
Dissolved nitrate	e	20	0.55	0.65	0.085	0.27	0.70	
	b	11	0.51	0.74	0.040	0.11	0.85	0.5429
Total organic nitrogen	e	20	1.3	0.59	0.87	0.99	1.5	
	b	11	1.3	0.59	0.90	1.2	1.7	0.6491
Total phosphorus	e	20	0.077	0.034	0.040	0.070	0.095	
	b	11	0.070	0.044	0.030	0.080	0.11	0.6779
Dissolved orthophosphate	e	20	0.015	0.0089	0.010	0.010	0.015	
	b	11	0.010	0.001	0.010	0.010	0.010	0.0803
Total organic phosphorus	e	20	0.061	0.037	0.030	0.050	0.085	
	b	11	0.060	0.044	0.020	0.070	0.095	0.8355

detection levels by early September. During periods of inflow, reservoir water quality was influenced slightly by inflowing water from the South Platte River. Between March and June, concentrations of both nitrate and total nitrogen decreased overall at the South Platte River at Balzac (fig. 3), the nearest monitoring station to the Prewitt Reservoir intakes. These decreases in river concentrations contributed to a decrease in reservoir concentrations during that period, though the influence of the river water likely was minor compared to internal processes during April through June, as inflow volumes during that period were small compared to the volume in storage. After reservoir inflows had ended entirely in mid-July, continued biological activity resulted in assimilation of all remaining nitrate by September, and only total organic nitrogen was left in measurable quantities.

Median concentrations of total phosphorus for all data combined were lowest in August, at 0.03 mg/L, and highest in March, at 0.12 mg/L (fig. 17). The temporal pattern of total phosphorus concentrations in the reservoir during periods of inflow appeared to follow that of the South Platte River at Balzac (fig. 3), indicating that inflow loading influenced concentrations of phosphorus in the reservoir. However, as with nitrogen, the influence of the river water likely was minor compared to internal processes. After reservoir inflows had ended entirely in mid-July, biological activity continued, but concentrations increased by September due to internal recycling.

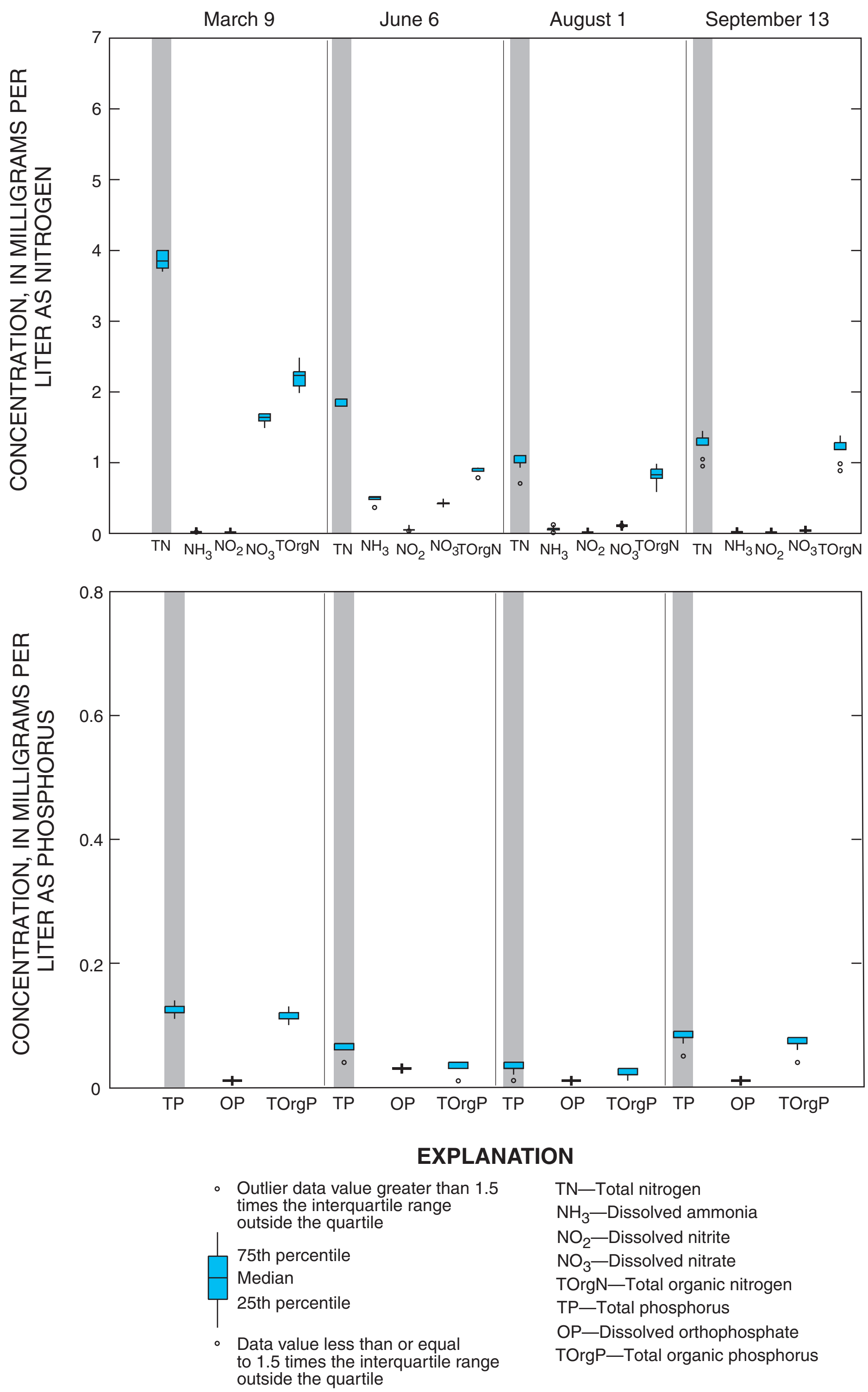


Figure 17. Nitrogen and phosphorus concentrations, euphotic and bottom samples combined in Prewitt Reservoir, March–September 1995.

Bottom-Sediment Flux

Estimates of nutrient flux from the bottom sediment indicate that the sediment was, at times, a potential source of nutrients to the reservoir. On March 9, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at sites 1 and 2 (fig. 18). The estimated flux rates for inorganic nitrogen were 35 $mg/m^2/d$ at site 1 and 88 $mg/m^2/d$ at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at sites 1 and 2 on March 21. The estimated flux rate for orthophosphate was 1.7 $mg/m^2/d$ at site 1 and 4.3 $mg/m^2/d$ at site 2. On August 17, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at sites 1 and 2. The estimated flux rates for inorganic nitrogen were 142 $mg/m^2/d$ at site 1 and 116 $mg/m^2/d$ at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at sites 1 and 2 on August 17. The estimated flux rates for orthophosphate were 9.9 $mg/m^2/d$ at site 1 and 10 $mg/m^2/d$ at site 2. The bottom dissolved oxygen concentrations at site 1 and site 2 on March 9 were close to 15 mg/L; concentrations on August 17 fell somewhere between 5 mg/L, the minimum measured on August 1, and 7 mg/L, measured on September 13. Because bottom sediment release is redox-dependent, movement from the sediment into the overlying water column is restricted if the sediment/water interface is well oxygenated (Horne and Goldman, 1994). Therefore, these flux calculations may overestimate the movement of nutrients from bottom sediment to the water column.

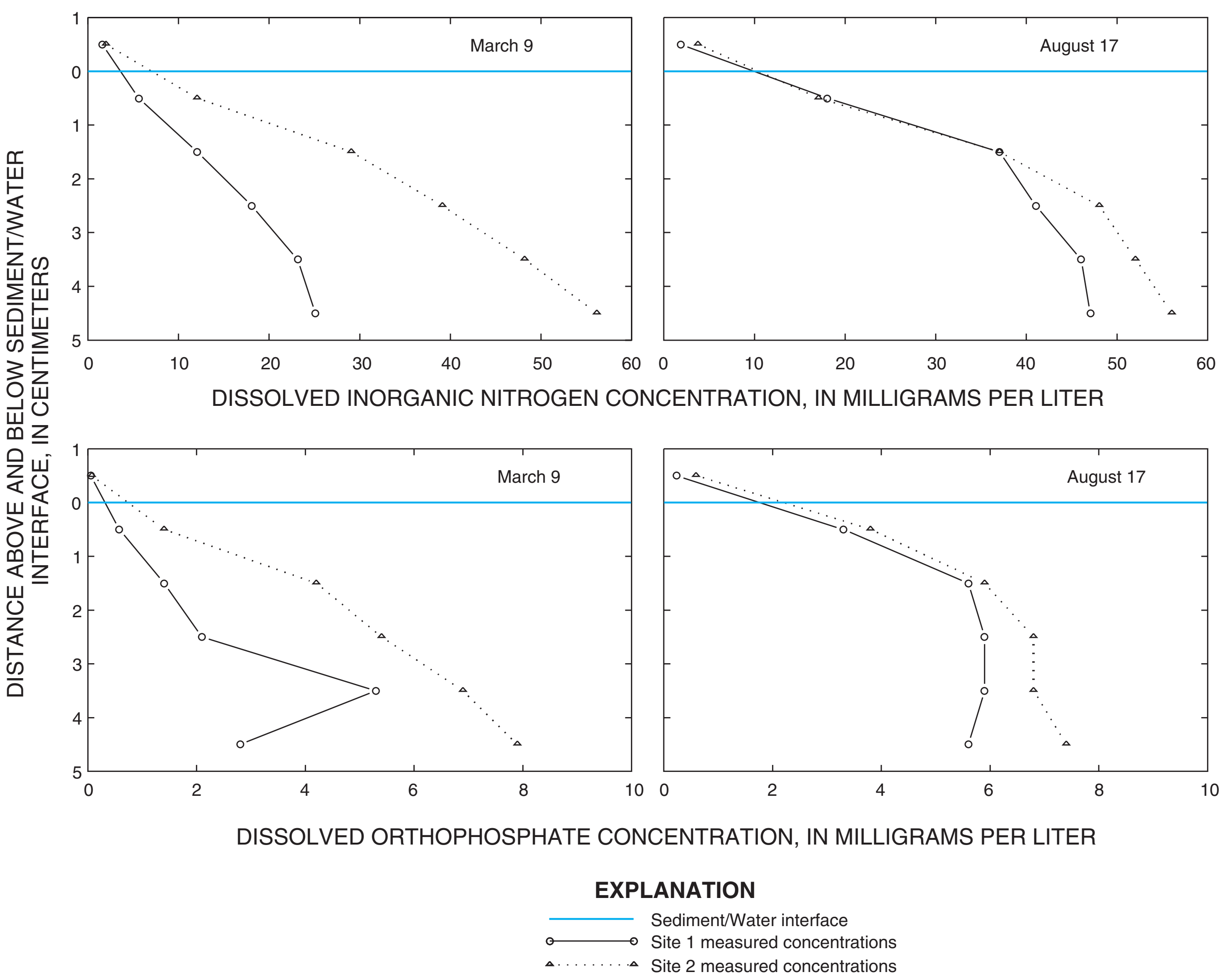


Figure 18. Concentrations of dissolved inorganic nitrogen and orthophosphate in bottom-sediment pore water and the overlying water column in Prewitt Reservoir, March 9 and August 17, 1995.

Mass Balance

Mass-balance calculations for nitrogen indicate that about 88 percent of the total mass of nitrogen—the mass that had been in storage in March plus the mass that had entered in inflows through September—was trapped in the reservoir (represented by the "unaccounted for" term), while less than 1 percent was released through the outflow (table 16). Only 12 percent of the mass remained in the water column by September. Mass-balance calculations for phosphorus indicate that about 86 percent of the total mass of phosphorus was trapped in the reservoir, while less than 1 percent was released through the outflow. Only 14 percent of the mass remained in the water column by September.

Much of the nitrogen was trapped in the reservoir through biological uptake and deposition of particulate organic nitrogen onto bottom sediment. Though phosphorus likely was internally recycled due to processes such as excretion from zooplankton and fish, decay of aquatic plants and animals, and release from bottom sediment, much of the total mass was trapped due to sedimentation. The residence time of water in Prewitt Reservoir was on the order of 2 to 3 years, and sedimentary losses of phosphorus and nitrogen typically are higher within reservoirs with longer residence times than in more rapidly flushed reservoirs (Kennedy and Walker, 1990). Additionally, because little outflow occurred during the study period, the mass lost in outflowing water was very small. Overall, a substantial portion of the total nutrient mass was trapped in the reservoir during the study period, and the reservoir acted as a sink for both nitrogen and phosphorus.

Algal Growth

The nutrient dynamics in the reservoir may have led to a change in the nutrients limiting algal growth. In March, August, and September, dissolved orthophosphate concentrations were below the algal growth-limiting concentration of 0.010 mg/L (table 17), indicating that phosphorus was potentially the limiting nutrient in those months. In September, concentrations of dissolved inorganic nitrogen species

Table 16. Mass-balance calculations for total nitrogen and total phosphorus in Prewitt Reservoir, March–September 1995

[From equation 1: Unaccounted for mass = Final storage mass – Initial storage mass – Inflow mass + Outflow mass]

Date	Total nitrogen mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 9	120,122				
March 10–May 10		115,347	0		
May 11–June 6		9,355	0		
June 7–July 11		11,324	0		
July 12–August 17		821	784		
August 18–September 13		0	0		
September 11				31,118	
Total	120,122	136,847	784	31,118	–225,067

Date	Total phosphorus mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 9	3,698				
March 10–May 10		7,263	0		
May 11–June 6		985	0		
June 7–July 11		2,427	0		
July 12–August 17		155	50		
August 18–September 13		0	0		
September 11				1,992	
Total	3,698	10,829	50	1,992	–12,487

Table 17. Concentrations of biologically available nitrogen and phosphorus and N:P values for Prewitt Reservoir, March–September 1995

[<, less than; --, missing data; DIN, dissolved inorganic nitrogen; DOP, dissolved orthophosphate; N:P, mass ratio of nitrogen to phosphorus; values of N:P calculated from total nitrogen and total phosphorus if DIN or DOP concentrations below detection limits]

Site (figure 14)	Concentration, in milligrams per liter		N:P
	DIN	DOP	
	March 9		
1	1.6	< 0.010	31
2	1.7	< 0.010	31
3	1.6	< 0.010	32
4	1.7	< 0.010	34
5	1.5	< 0.010	29
	June 6		
1	0.99	< 0.030	33
2	1.0	< 0.030	33
3	1.0	< 0.030	33
4	0.94	< 0.030	31
5	0.85	< 0.030	28
	August 1		
1	0.19	< 0.010	25
2	0.20	< 0.010	25
3	0.13	< 0.010	27
4	0.20	< 0.010	23
5	0.13	< 0.010	24
	September 13		
1	<0.065	< 0.010	16
2	<0.065	< 0.010	15
3	<0.065	< 0.010	16
4	<0.065	< 0.010	16
5	<0.065	< 0.010	15

and dissolved orthophosphate were all below the detection limit, suggesting that both phosphorus and nitrogen were limiting by the end of the study period. Values of N:P indicate that phosphorus was the limiting nutrient throughout the entire study period. In March, N:P values ranged from 29 to 34; in June, N:P values ranged from 28 to 33; in August, N:P values ranged from 23 to 27; and in September, N:P values ranged from 15 to 16. Because blue-green algae are less common when N:P values exceed 29 (Ryding and Rast, 1989), green algae likely predominated over blue-green algae until September.

Although chlorophyll-*a* measurements cannot provide information on the composition of the phytoplankton community, they can provide a measure of the quantity of algae present. Chlorophyll-*a* concentrations measured in the euphotic zone in June ranged from 1.2 µg/L at site 2 to 1.6 µg/L at sites 1 and 4 (table 18). By early August, chlorophyll-*a* concentrations ranged from 17 µg/L at site 2 to 23 µg/L at sites 1 and 4. By September, chlorophyll-*a* concentrations ranged from 35 µg/L at site 1 to 40 µg/L at site 2. Based on mean chlorophyll-*a* concentrations, Prewitt Reservoir is classified as eutrophic. Carlson's chlorophyll TSI values ranged from 41 to 44 in June, from 67 to 70 in August, and from 74 to 76 in September (table 18), indicating that the algal biomass doubled approximately three times during the spring and summer.

Table 18. Chlorophyll-*a* concentrations, Secchi-disk depths, total phosphorus concentrations, and associated trophic-state indices for Prewitt Reservoir, March–September 1995

[µg/L, micrograms per liter; mg/L; milligrams per liter; TSI, Trophic State Index, Chl, chlorophyll-*a*; SD, Secchi disk; TP, total phosphorus]

Site (figure 14)	Chlorophyll-*a* concentration (µg/L)	TSI(Chl)	Secchi-disk depth (feet)	TSI(SD)	Total phosphorus concentration (mg/L)	TSI(TP)
			June 6			
1	1.6	44	7.5	48	0.070	65
2	1.2	41	10	44	0.040	57
4	1.6	44	4.5	55	0.070	65
			August 1			
1	23	70	3.0	61	0.040	57
2	17	67	3.0	61	0.040	57
4	23	70	2.5	64	0.040	57
			September 13			
1	35	74	2.0	67	0.080	67
2	40	76	2.0	67	0.070	65
4	37	75	2.0	67	0.090	69

NORTH STERLING RESERVOIR

North Sterling Reservoir is in Logan County, Colo., approximately 10 mi northwest of Sterling (fig. 1). It is owned by North Sterling Irrigation District and also is operated as a State Park by the Colorado Division of Parks and Outdoor Recreation. The reservoir has an estimated maximum storage capacity of 74,010 acre-ft and receives most of its surface-water inflow from North Sterling Canal (fig. 19), which originates in the South Platte River upstream from Sterling. Additional surface water enters the reservoir during storms through Cedar Creek, an ephemeral stream on the northwest side of the reservoir. Water released from the reservoir through North Sterling Outlet Canal is used primarily for irrigation; other uses include recreation.

During the study period, reservoir storage ranged from 70,883 acre-ft in March to 9,820 acre-ft in September (fig. 20 and table 19) and maximum depth ranged from about 52 ft in March to about 24 ft in September. The reservoir normally is filled during the fall and winter, reaching maximum volumes in the early spring. In 1995, the reservoir reached maximum storage in April, and water was released for irrigation beginning in May. Most of the outflow occurred from July through September as demand for irrigation water increased; maximum outflow occurred during July. Correspondingly, storage volumes dropped sharply from July through September. Measurable residence times in the reservoir ranged from 47 days in July to 26 days in September as outflow increased and storage decreased (table 19).

Water-quality samples were collected at six sites throughout the reservoir (fig. 19) on March 10, June 1, July 27, and September 14, 1995 (site 6 could not be sampled on September 14 due to lack of water). Samples for chlorophyll-*a* were collected only on the last three dates from sites 1, 2, and 3. Additional water-quality samples were collected from North Sterling Canal and North Sterling Outlet (when flowing) on March 10, May 11, July 11, August 16, and September 14, 1995. Bottom-sediment samples were collected from sites 1 and 2 on March 21 and August 16, 1995.

Water Temperature and Dissolved Oxygen

The temperature profile for March 10 indicates that the reservoir was well mixed at all sites in the late winter, with the exception of slight surface warming at site 6 (fig. 21). At temperatures near 3ºC from surface to bottom, very little wind energy would have been necessary to mix the water column. As spring progressed, all sites became weakly stratified due to increased solar heating of surface water and the inflow of warmer water from North Sterling Canal as overflow at the reservoir surface. By late July, the deeper sites (1, 2, 4, 5) were strongly stratified due to heating and density differences with depth. Although the surrounding terrain is relatively flat and strong winds are common, the reservoir likely was deep enough through August that there was insufficient energy to overcome stratification. Removal of a large volume of water and increased evaporative cooling during the period from July 27 to September 14 resulted in a weaker temperature and density gradient between surface water and bottom water by mid-September, increasing mixing and reducing the degree of stratification at all sites. As a result, all sites were well mixed and isothermal by late summer.

Dissolved oxygen concentrations during the study period were highest in March when water temperatures were lowest. On March 10, the reservoir was well mixed and oxygen was uniformly distributed with depth at all sites except site 6 (fig. 21). Supersaturation of dissolved oxygen at site 6 indicated photosynthetic activity in the shallow southern arm of the reservoir; enhanced primary productivity often occurs early in the growing season in reservoir embayments isolated from flow perturbations (Kimmel and others, 1990). Reduced dissolved oxygen concentrations first were observed in early June at all sites due to biological oxidation of sinking organic matter. Oxygen in the hypolimnion became progressively more depleted and reached anoxic levels by the end of July as more organic matter sank to bottom depths. Summer hypolimnetic oxygen in highly productive lakes commonly is depleted after only a few weeks of stratification (Wetzel, 1983). By September, the reservoir was shallow and well mixed, though slightly reduced oxygen conditions remained in the bottom water, where the rate of consumptive metabolism continued to exceed photosynthetic inputs at the surface.

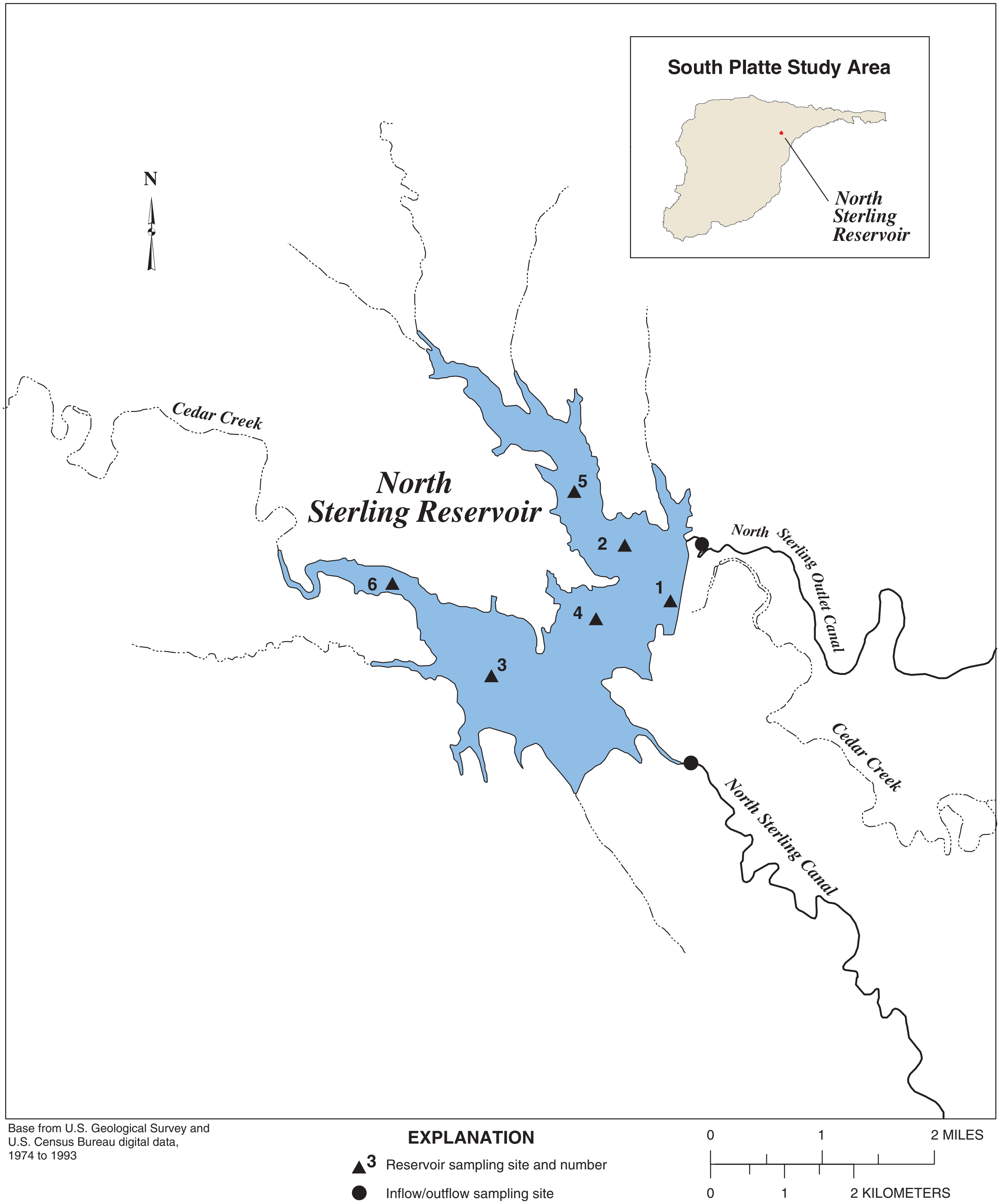


Figure 19. Location of sampling sites in North Sterling Reservoir.

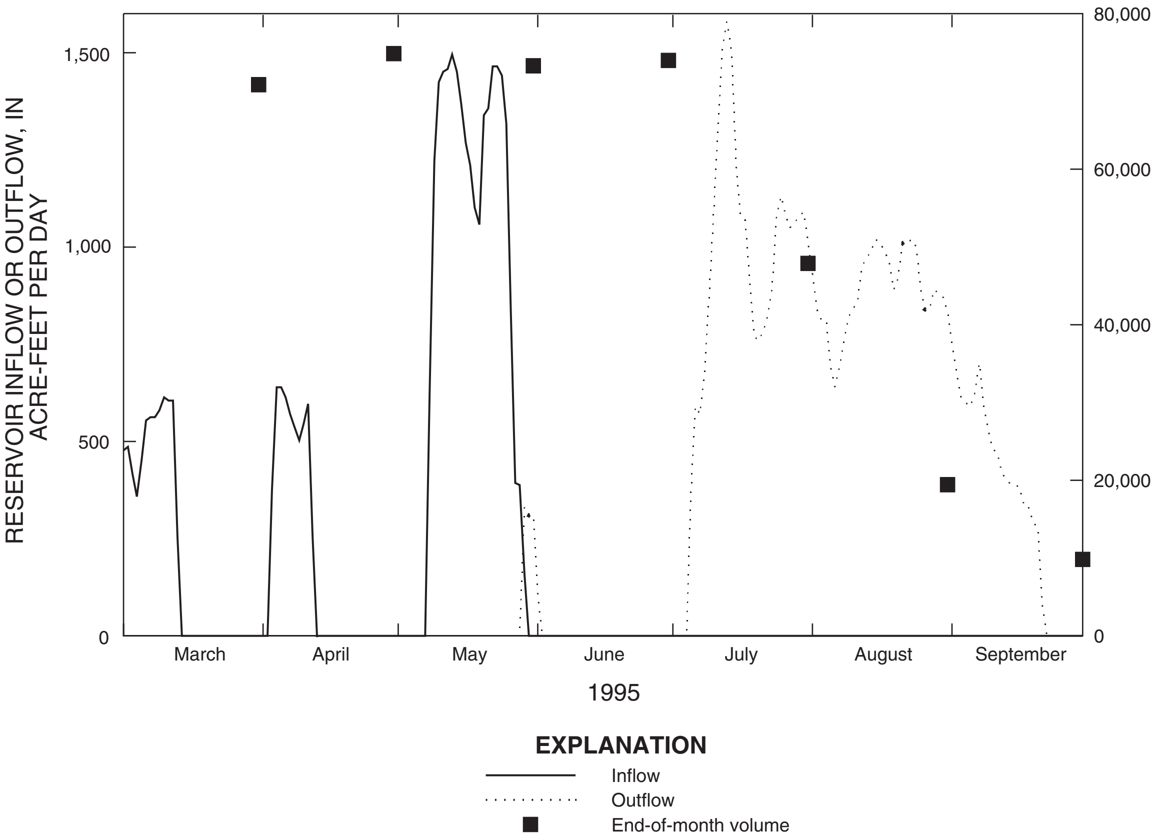


Figure 20. Inflow, outflow, and end-of-month storage volume in North Sterling Reservoir, March–September 1995.

Table 19. End-of-month storage, monthly median outflow, and residence time in North Sterling Reservoir, March–September 1995

[acre-ft, acre-feet; acre-ft/d, acre-feet per day; --, could not be calculated]

Month	End-of-month storage (acre-ft)	Monthly median outflow (acre-ft/d)	Residence time (days)
March	70,883	0	--
April	74,876	0	--
May	73,300	0	--
June	74,010	0	--
July	47,893	1,010	47
August	19,440	890	22
September	9,820	385	26

pH and Specific Conductance

In North Sterling Reservoir, pH ranged seasonally between 7.4 and 8.6 (fig. 21). On March 10 and June 1, pH was constant from surface to bottom at all six sites. A slight gradient in pH values was present on July 27 and September 14 due to photosynthesis, which tends to increase pH near the surface, and decomposition, which tends to decrease pH near the bottom, though these effects were buffered by bicarbonate and carbonate. On all sampling dates, specific conductance was constant from surface to bottom at all six sites (fig. 21). The maximum specific conductance measured during the study period was approximately 1,780 μS/cm on March 10. At this time, specific conductance was influenced primarily by inflow water; specific conductance was measured at 1,827 μS/cm in North Sterling Canal that day. After inflows ended in late May, specific conductance decreased slightly. Because of the high salinity, use of this water for irrigation could have been detrimental to crop quality and yield.

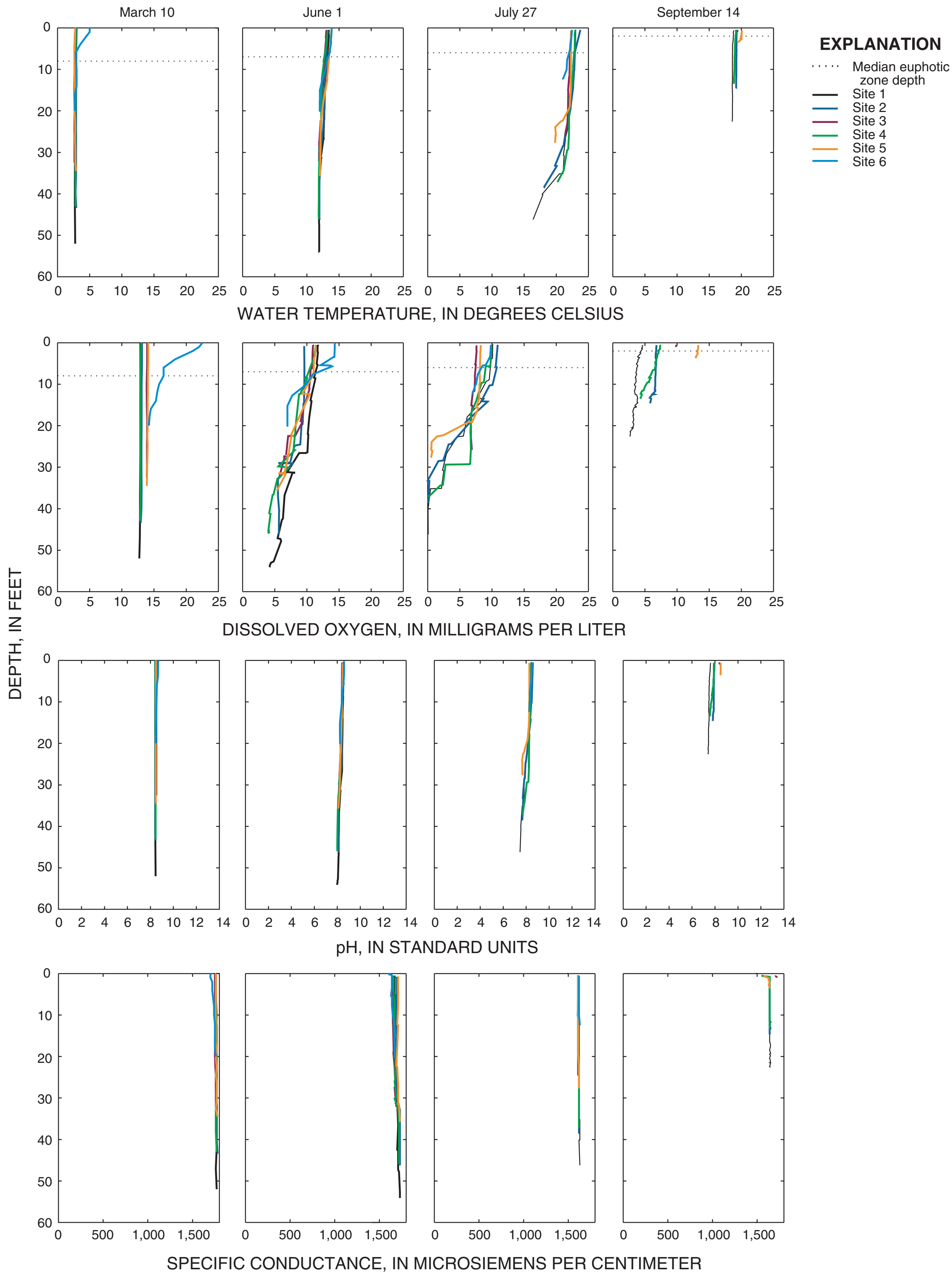


Figure 21. Depth profiles of water temperature, dissolved oxygen, pH, and specific conductance in North Sterling Reservoir, March–September 1995.

Nutrient Dynamics

Water-Column Concentrations

A statistical summary of nutrient concentrations at the six sites sampled in North Sterling Reservoir, including both euphotic and bottom samples, is provided in table 20. Median concentrations of total nitrogen during the study period ranged from 2.7 mg/L at sites 2 and 4 to 3.5 mg/L at site 6. Median concentrations of total phosphorus during the study period ranged from 0.060 mg/L at site 3 to 0.15 mg/L at sites 1 and 2. A statistical analysis of nutrient concentrations using the Kruskal-Wallis test indicates that the differences in nutrient concentrations between the sites were not significant (α=0.05). Because the outflow volumes were large, residence times were short, resulting in a minimal longitudinal gradient.

Observed concentrations for all samples collected near the reservoir surface and near the reservoir bottom were significantly different for some constituents during the study period (table 21). Results of a Wilcoxon Rank-Sum test indicate that concentrations of nutrient species that are most readily available to biota—dissolved orthophosphate and dissolved ammonia—were significantly lower (α=0.05) near the surface due to biological activity in the euphotic zone and release from bottom sediment. Additionally, concentrations of total organic nitrogen were significantly higher near the surface, likely due to assimilation in plankton and secretion by aquatic plants and animals present in the euphotic zone. The variation with depth likely was because the reservoir developed strong stratification to limit mixing between surface water and bottom water during the summer.

In addition to the vertical variability in nutrient concentrations, results of a Kruskal-Wallis test indicate that there was significant (α=0.05) temporal variability in total nitrogen and total phosphorus concentrations from March through September (fig. 22). Median concentrations of total nitrogen in the euphotic zone decreased from 4.9 mg/L in March to 1.7 mg/L in September; median concentrations of total nitrogen near the bottom decreased from 4.8 mg/L in March to 1.4 mg/L in September. The decrease in total nitrogen throughout the water column was driven largely by a decrease in nitrate; median concentrations of nitrate dropped from 3.8 mg/L in March to below laboratory detection levels by September in the euphotic zone and near the bottom.

Reservoir water quality was influenced by conditions in the South Platte River during periods of inflow, particularly in the euphotic zone, as warmer river water entered as overflow. In March and April, concentrations of both nitrate and total nitrogen decreased at the South Platte River at Balzac (fig. 3), the monitoring station nearest to the North Sterling Canal intake. The decreases in river concentrations contributed to a corresponding decrease in reservoir concentrations during March and April. However, concentrations of total nitrogen at Balzac remained level in May, whereas concentrations in the reservoir continued to decrease. This suggests that biological activity also was contributing to the decline in nitrogen concentrations and that the rate of nitrate assimilation by algae had exceeded the rate of nitrate inflow by May. After reservoir inflows had ended entirely at the end of May, continued biological activity resulted in assimilation of all remaining nitrate, and only total organic nitrogen was left in measurable quantities in the euphotic zone. Additionally, ammonia was present in the bottom water in the June, July, and September samples, likely due to release from the bottom sediment under anoxic conditions. Ammonia in the hypolimnion may have reached the epilimnion during storm-induced turbulence near the top of the thermocline or during hypolimnetic entrainment (Horne and Goldman, 1994) and thereby been available for biological uptake or nitrification in the euphotic zone.

Concentrations of total phosphorus did not have the same consistent decrease during the study period as concentrations of total nitrogen. Median concentrations of total phosphorus in the euphotic zone ranged from 0.15 mg/L in March to 0.18 mg/L in September; median concentrations of total phosphorus near the bottom ranged from 0.13 mg/L in March to 0.17 mg/L in September (fig. 22). The temporal pattern of total phosphorus concentrations in the euphotic zone from March through May appeared to follow that of the South Platte River at Balzac (fig. 3), indicating that inflow loading influenced concentrations of phosphorus in the reservoir. After reservoir inflows ceased at the end of May, biological activity continued, but concentrations increased in both euphotic and bottom water by September due to internal recycling.

Bottom-Sediment Flux

Estimates of nutrient flux from the bottom sediment indicate that the sediments were, at times, a

Table 20. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in North Sterling Reservoir, March–September 1995

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 19)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	1	8	3.0	1.5	1.9	2.9	4.1	
	2	8	3.0	1.3	2.1	2.7	3.7	
	3	7	3.1	1.3	2.1	3.0	3.9	
	4	8	2.9	1.4	2.0	2.7	3.6	
	5	7	3.2	1.2	2.1	3.1	4.1	
	6	6	3.3	1.1	2.4	3.5	4.1	0.9980
Dissolved ammonia	1	8	0.39	0.63	0.037	0.19	0.35	
	2	8	0.21	0.22	0.045	0.16	0.24	
	3	7	0.12	0.12	0.017	0.050	0.21	
	4	8	0.17	0.20	0.037	0.070	0.25	
	5	7	0.099	0.097	0.020	0.070	0.15	
	6	6	0.073	0.085	0.023	0.040	0.073	0.4826
Dissolved nitrite	1	8	0.045	0.026	0.033	0.045	0.063	
	2	8	0.053	0.035	0.033	0.050	0.073	
	3	7	0.054	0.032	0.030	0.060	0.080	
	4	8	0.055	0.036	0.033	0.050	0.090	
	5	7	0.056	0.029	0.040	0.060	0.075	
	6	6	0.058	0.037	0.030	0.065	0.085	0.9665
Dissolved nitrate	1	8	1.6	1.6	0.0	1.5	2.6	
	2	8	1.7	1.5	0.6	1.6	2.5	
	3	7	1.9	1.4	1.0	2.0	2.9	
	4	8	1.8	1.5	0.7	1.6	2.6	
	5	7	1.9	1.4	0.87	2.0	2.9	
	6	6	2.0	0.95	1.2	2.0	2.6	0.9995
Total organic nitrogen	1	8	0.98	0.34	0.82	0.94	1.1	
	2	8	0.99	0.24	0.86	1.0	1.1	
	3	7	0.97	0.31	0.79	0.95	1.0	
	4	8	0.97	0.33	0.80	0.92	1.0	
	5	7	1.2	0.43	0.93	0.98	1.2	
	6	6	1.1	0.43	0.85	0.97	1.4	0.8813
Total phosphorus	1	8	0.18	0.17	0.12	0.15	0.16	
	2	8	0.12	0.060	0.058	0.15	0.17	
	3	7	0.090	0.058	0.045	0.060	0.14	
	4	8	0.11	0.055	0.073	0.11	0.16	
	5	7	0.11	0.066	0.070	0.090	0.14	
	6	6	0.080	0.028	0.055	0.080	0.098	0.4536

Table 20. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in North Sterling Reservoir, March–September 1995—Continued

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 19)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Dissolved orthophosphate	1	8	0.11	0.21	0.018	0.025	0.063	
	2	8	0.039	0.043	0.010	0.015	0.060	
	3	7	0.023	0.019	0.010	0.010	0.035	
	4	8	0.030	0.023	0.010	0.020	0.053	
	5	7	0.020	0.017	0.010	0.010	0.025	
	6	6	0.013	0.0082	0.010	0.010	0.010	0.8800
Total organic phosphorus	1	8	0.074	0.072	0.038	0.080	0.14	
	2	8	0.083	0.059	0.030	0.070	0.11	
	3	7	0.067	0.051	0.035	0.050	0.090	
	4	8	0.084	0.057	0.040	0.065	0.11	
	5	7	0.094	0.064	0.060	0.080	0.095	
	6	6	0.067	0.027	0.045	0.065	0.078	0.9702

Table 21. Statistical summary of nutrient concentrations in euphotic and bottom samples and results of Wilcoxon Rank-Sum test of euphotic and bottom concentration differences in North Sterling Reservoir, March–September 1995

[e, euphotic; b, bottom; all concentrations are in milligrams per liter; p-value represents the probability that e and b concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Location	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	e	23	3.1	1.2	2.1	3.1	4.1	
	b	21	3.1	1.3	2.0	3.2	4.3	0.9437
Dissolved ammonia	e	23	0.073	0.079	0.025	0.050	0.080	
	b	21	0.31	0.41	0.040	0.22	0.34	0.0031
Dissolved nitrite	e	23	0.050	0.030	0.020	0.060	0.070	
	b	21	0.057	0.031	0.040	0.060	0.090	0.3921
Dissolved nitrate	e	23	1.7	1.3	0.94	1.8	2.5	
	b	21	1.9	1.4	0.86	2.0	3.3	0.9155
Total organic nitrogen	e	23	1.2	0.36	0.94	1.1	1.5	
	b	21	0.86	0.20	0.76	0.82	0.98	0.0017
Total phosphorus	e	23	0.11	0.059	0.055	0.12	0.15	
	b	21	0.13	0.11	0.060	0.10	0.15	0.9906
Dissolved orthophosphate	e	23	0.020	0.019	0.010	0.010	0.015	
	b	21	0.062	0.13	0.010	0.030	0.050	0.0151
Total organic phosphorus	e	23	0.092	0.055	0.045	0.080	0.13	
	b	21	0.064	0.053	0.030	0.060	0.080	0.1138

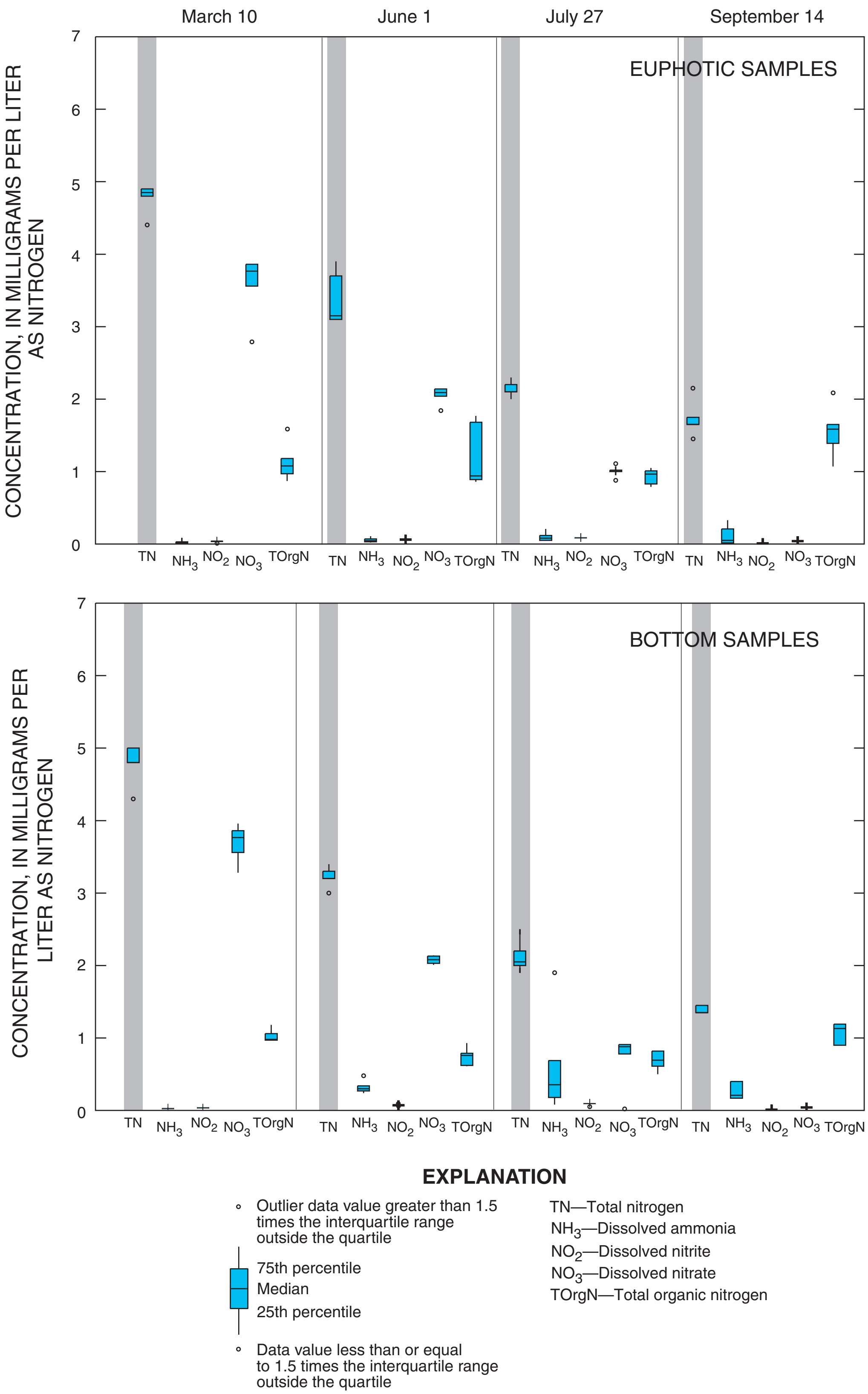


Figure 22. Nitrogen and phosphorus concentrations in euphotic and bottom samples in North Sterling Reservoir, March–September 1995.

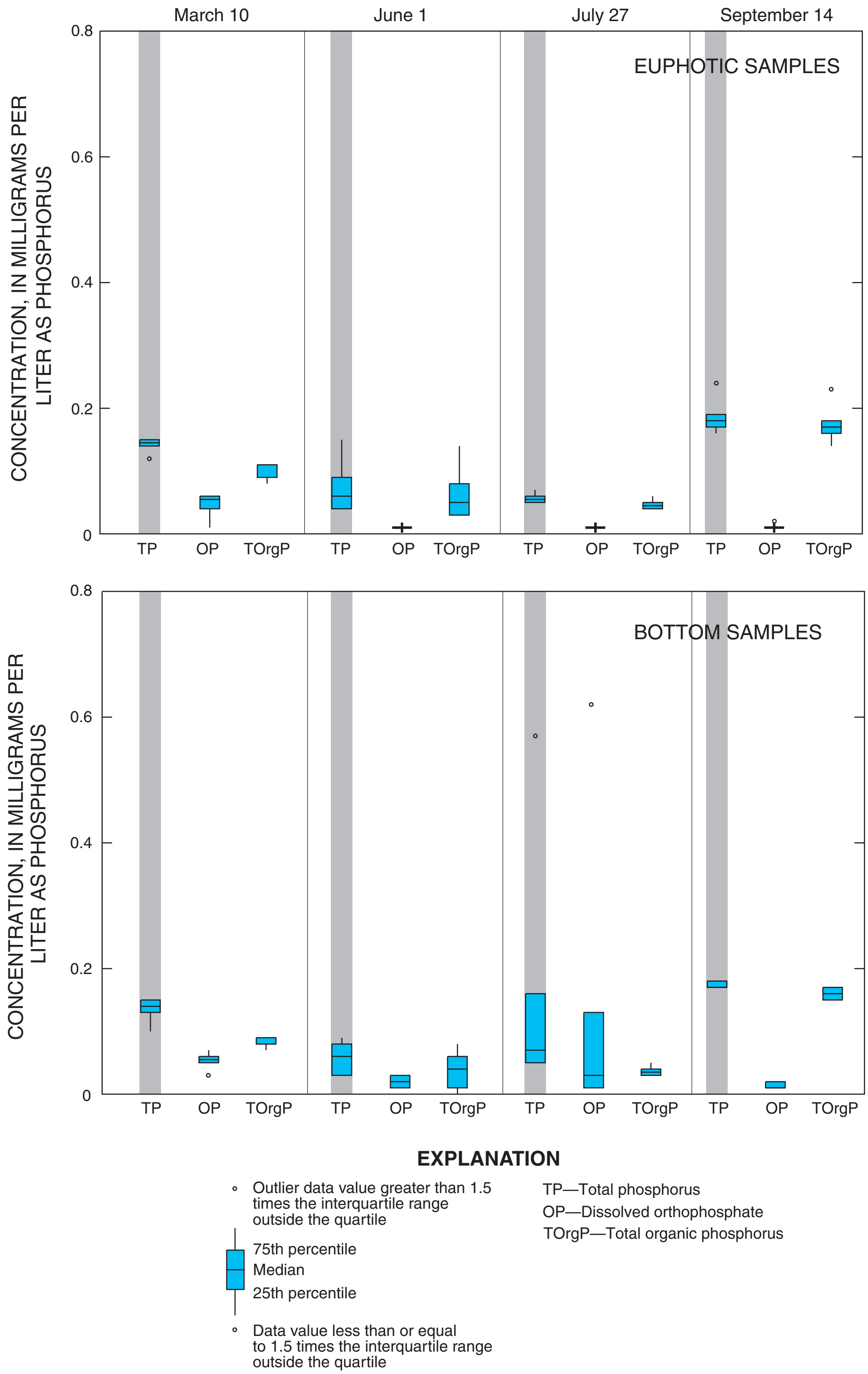


Figure 22. Nitrogen and phosphorus concentrations in euphotic and bottom samples in North Sterling Reservoir, March–September 1995—Continued

potential source of nutrients to the reservoir. On March 21, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were lower than in the overlying water column at sites 1 and 2 (fig. 23). The estimated flux rates for inorganic nitrogen were –17 mg/m^2/d at site 1 and –8.8 mg/m^2/d at site 2 (both into the sediment). Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment were similar to those in the overlying water column at site 1 and higher than in the overlying water column at site 2 on March 21. The estimated flux rate for orthophosphate was 0 mg/m^2/d at site 1 and 1.9 mg/m^2/d at site 2. On August 16, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at sites 1 and 2. The estimated flux rates for inorganic nitrogen were 80 mg/m^2/d at site 1 and 53 mg/m^2/d at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at sites 1 and 2 on August 16. The estimated flux rates for orthophosphate were 28 mg/m^2/d at site 1 and 23 mg/m^2/d at site 2. The bottom dissolved oxygen concentrations at site 1 and site 2 on March 10 were close to 13 mg/L; concentrations on August 17 fell somewhere between 0 mg/L, the minimum measured on July 27, and 3 mg/L, measured on September 14. Under the oxygenated conditions in March, the flux of dissolved inorganic nitrogen was into the sediments and the rate

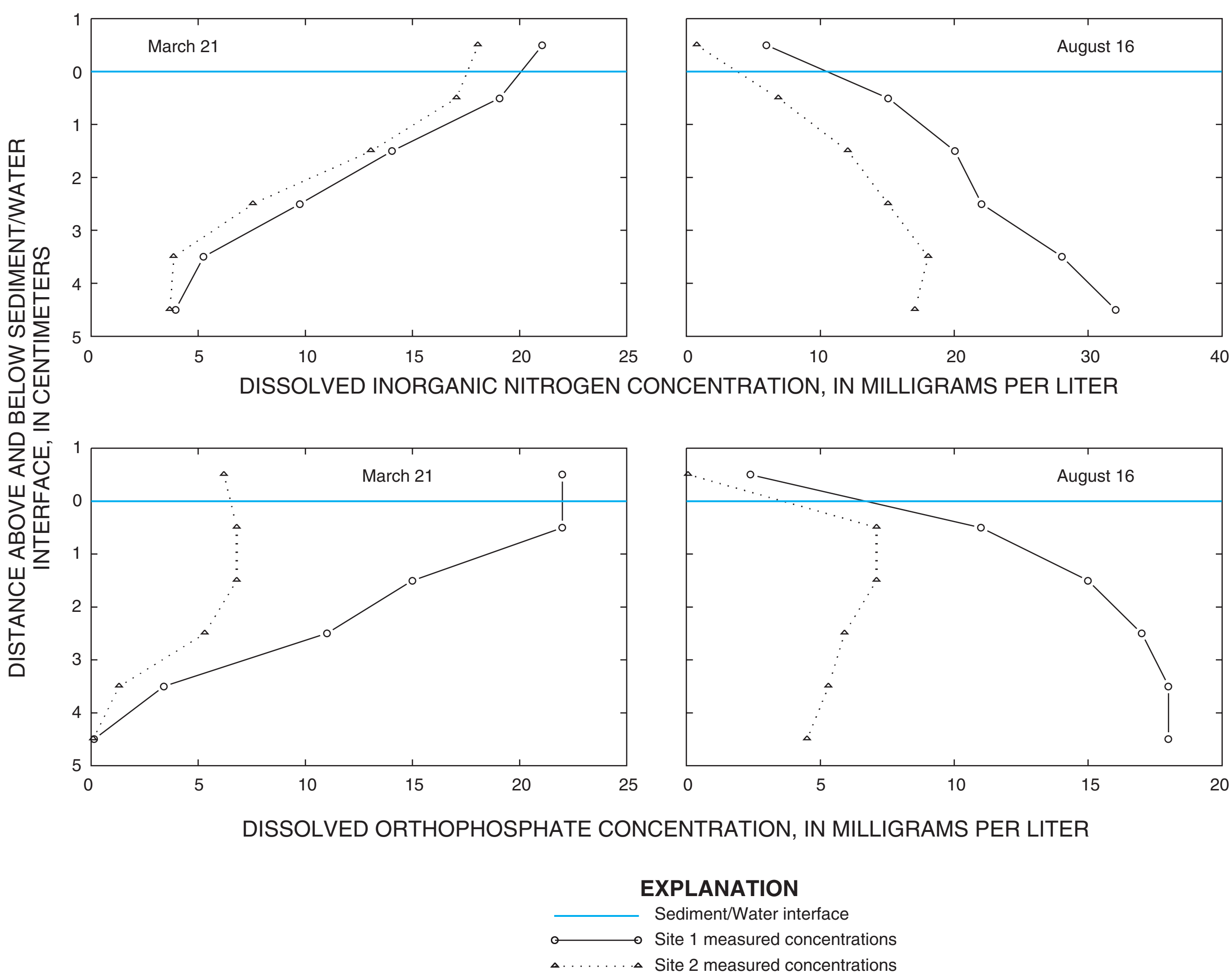


Figure 23. Concentrations of dissolved inorganic nitrogen and orthophosphate in bottom-sediment pore water and the overlying water column in North Sterling Reservoir, March 21 and August 16, 1995.

of dissolved orthophosphate flux into the overlying water column was small. Under the anoxic conditions in mid-August, the flux of both constituents was into the overlying water column, and the rates had increased.

Mass Balance

Mass-balance calculations for nitrogen indicate that about 59 percent of the total mass of nitrogen—the mass that had been in storage in March plus the mass that had entered in inflows through September —was trapped in the reservoir (represented by the "unaccounted for" term), while 37 percent was released through the outflow (table 22). Only 4 percent of the mass remained in the water column by September. Mass-balance calculations for phosphorus indicate that about 42 percent of the total mass of phosphorus was trapped in the reservoir, while 47 percent was released through the outflow. Only about 12 percent of the mass remained in the water column by September. Much of the nitrogen was trapped in the reservoir through biological uptake and deposition of particulate organic nitrogen onto bottom sediments. Much of the phosphorus was trapped through sedimentation of orthophosphate adsorbed to inorganic particles, deposition of particulate organic phosphorus onto bottom sediment, and biological uptake. From July through September, the reservoir had short residence times, and some of the nitrogen and recycled phosphorus still in the water column was flushed out. Overall, a substantial portion of the total nutrient mass was trapped in the reservoir during the study period, and the reservoir acted as a sink for both nitrogen and phosphorus.

Algal Growth

In June, July, and September, dissolved orthophosphate concentrations were below the algal growth-limiting concentration of 0.010 mg/L at most sites (table 23), indicating that phosphorus was potentially the limiting nutrient in those months. In September, concentrations of dissolved inorganic nitrogen were below the detection limit at some sites as well, suggesting that both phosphorus and nitrogen were limiting by the end of the study period. Values of N:P indicate that phosphorus was the limiting nutrient throughout the entire study period. In March, N:P values ranged from 37 to 90; in June, N:P values ranged from 26 to 80; in July, N:P values ranged from 30 to 46; and in September, N:P values ranged from

Table 22. Mass-balance calculations for total nitrogen and total phosphorus in North Sterling Reservoir, March–September 1995

[From equation 1: Unaccounted for mass = Final storage mass – Initial storage mass – Inflow mass + Outflow mass]

Date	Total nitrogen mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 10	424,228				
March 11–May 11		62,824	18,401		
May 12–July 11		0	54,029		
July 12–August 16		0	69,301		
August 17–September 14		0	40,230		
September 14				18,540	
Total	424,228	62,824	181,962	18,540	–286,549

Date	Total phosphorus mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 10	12,683				
March 11–May 11		5,711	345		
May 12–July 11		0	1,455		
July 12–August 16		0	3,898		
August 17–September 14		0	2,931		
September 14				2,121	
Total	12,683	5,711	8,628	2,121	–7,645

Table 23. Concentrations of biologically available nitrogen and phosphorus and N:P values for North Sterling Reservoir, March–September 1995

[<, less than; --, missing data; DIN, dissolved inorganic nitrogen; DOP, dissolved orthophosphate; N:P, mass ratio of nitrogen to phosphorus; values of N:P calculated from total nitrogen and total phosphorus if DIN or DOP concentrations below detection limits]

Site (figure 19)	Concentration, in milligrams per liter		N:P
	DIN	DOP	
	March 10		
1	3.9	0.060	65
2	3.8	0.060	64
3	3.8	0.050	76
4	3.9	0.060	65
5	3.6	0.040	90
6	2.8	< 0.010	37
	June 1		
1	2.2	< 0.010	26
2	2.3	< 0.010	80
3	2.1	< 0.010	77
4	2.2	< 0.010	62
5	2.2	< 0.010	44
6	1.9	< 0.010	41
	July 27		
1	1.2	< 0.010	33
2	1.1	< 0.010	37
3	1.3	< 0.010	42
4	1.3	< 0.010	46
5	1.1	< 0.010	30
6	1.1	< 0.010	42
	September 14		
1	0.38	0.020	19
2	0.26	< 0.010	9.2
3	< 0.065	< 0.010	9.7
4	0.10	< 0.010	9.2
5	< 0.065	< 0.010	9.0
6	--	--	--

9.0 to 19. Because blue-green algae are less common when N:P values exceed 29, green algae likely predominated over blue-green algae until September (Ryding and Rast, 1989).

Although chlorophyll-*a* measurements cannot provide information on the composition of the phytoplankton community, they can provide a measure of the quantity of algae present. Chlorophyll-*a* concentrations measured in the euphotic zone in June ranged from 16 µg/L at site 2 to 26 µg/L at sites 1 and 3 (table 24). In late July, chlorophyll-*a* concentrations ranged from 12 µg/L at site 1 to 21 µg/L at site 2. By September, algal biomass had increased substantially; chlorophyll-*a* concentrations ranged from 32 µg/L at site 1 to 96 µg/L at site 3. Based on mean chlorophyll-*a* concentrations, North Sterling Reservoir is classified as eutrophic. Carlson's chlorophyll TSI values ranged from 67 to 72 in June, from 64 to 69 in July, and from 74 to 84 in September (table 24), indicating that the algal biomass approximately doubled from late spring to late summer. The chlorophyll, Secchi-disk, and phosphorus TSI values were similar, particularly in the summer, supporting the conclusion that phosphorus was the limiting nutrient during this period.

JULESBURG RESERVOIR

Julesburg Reservoir is in Logan and Sedgwick Counties, Colo., about 20 mi southwest of Julesburg (fig. 1). It is owned by Julesburg Irrigation District and also is operated as a State Wildlife Area by the Colorado Division of Wildlife. The reservoir has an estimated maximum storage capacity of 31,800 acre-ft and receives most of its surface-water inflow from Harmony Ditch (fig. 24), which originates in the South Platte River. Water released from the reservoir through Highline Canal is used primarily for irrigation.

During the study period, reservoir storage ranged from 22,666 acre-ft in March to 6,168 acre-ft in September (fig. 25 and table 25) and maximum depth ranged from about 18 ft in March to about 3 ft in September. The reservoir normally is filled during the fall and winter, reaching maximum volumes in the early spring. In 1995, the reservoir reached maximum storage in March and water was released for irrigation beginning in May. There were inflows during March and the end of September and outflows from May through September. Correspondingly, storage volumes during the study period decreased through the beginning of September then increased slightly through the end of September. Measurable residence times in the reservoir ranged from 180 days in June to 15 days in August as outflow increased and storage decreased (table 25).

Water-quality samples were collected at five sites throughout the reservoir (fig. 24) on March 23, June 2, July 28, and September 15, 1995. Water-quality samples at sites 1 and 5 and depth profiles of water temperature, dissolved oxygen, pH, and specific conductance at all five sites were not obtained on September 15 because the reservoir was extremely

Table 24. Chlorophyll-*a* concentrations, Secchi-disk depths, total phosphorus concentrations, and associated trophic-state indices for North Sterling Reservoir, March–September 1995

[µg/L, micrograms per liter; mg/L; milligrams per liter; TSI, Trophic State Index, Chl, chlorophyll-*a*; SD, Secchi disk; TP, total phosphorus]

Site (figure 19)	Chlorophyll-*a* concentration (µg/L)	TSI(Chl)	Secchi-disk depth (feet)	TSI(SD)	Total phosphorus concentration (mg/L)	TSI(TP)
			June 1			
1	26	72	3.5	59	0.15	76
2	16	67	4.0	57	0.040	57
3	26	72	3.5	59	0.040	57
			July 27			
1	12	64	3.0	61	0.060	63
2	21	69	3.0	61	0.060	63
3	14	65	3.0	61	0.050	61
			September 14			
1	32	74	1.0	77	0.16	77
2	65	81	1.0	77	0.18	79
3	96	84	0.50	87	0.17	78

shallow. Samples for chlorophyll-*a* were collected on June 2 and July 28 from sites 1, 2, and 3; samples on September 15 were collected from sites 2, 3, and 4. Additional water-quality samples were collected from Harmony Ditch and Highline Canal (when flowing) on March 23, June 2, July 10, August 15, and September 15, 1995. Bottom-sediment samples were collected from sites 1 and 2 in the early spring, on March 22 and April 4, and in the summer, on August 15.

Water Temperature and Dissolved Oxygen

The temperature profile for March 23 indicates that the reservoir was well mixed at all sites in late winter; temperatures were approximately 9ºC from surface to bottom (fig. 26). As spring and summer progressed, the water column remained nearly isothermal and no stratification was observed. Stratification from warmer inflow water entering as overflow did not occur, as there was no inflow during this period. Additionally, because the reservoir is relatively shallow and the surrounding terrain is flat, frequent strong winds helped keep the water column well mixed during the study period. On March 23 and June 2, oxygen was uniformly distributed with depth at all five sites (fig. 26). Slightly reduced dissolved oxygen concentrations with depth first were observed on June 2 at sites 1, 2, and 4 due to biological decomposition of sinking organic matter. A zone of low dissolved oxygen may have appeared first at the main sedimentation zone near the outlet at site 4 and begun to spread upreservoir to sites 1 and 2 by June 2 (Cole and Hannan, 1990). The lack of inflow during June and July promoted the upreservoir progression of low dissolved oxygen conditions; by July 28, a stronger vertical gradient of dissolved oxygen existed at all sites. Though the reservoir was well mixed at this time, rates of consumptive metabolism near the bottom were high enough to decrease bottom dissolved oxygen concentrations.

pH and Specific Conductance

In Julesburg Reservoir, pH ranged seasonally between 8.0 and 8.6 (fig. 26). On all sampling dates, pH was constant from surface to bottom at all five sites. The lack of a pH difference between zones of photosynthesis and decomposition indicates that the system was well buffered by bicarbonate and carbonate, preventing large changes in pH, and that it likely was well mixed by wind. On all sampling dates, specific conductance also was constant from surface to bottom at all five sites (fig. 26). The maximum specific conductance measured during the study period was approximately 2,030 µS/cm on March 23. At this time, specific conductance was influenced primarily by inflow water; specific conductance was measured at 2,020 µS/cm in Harmony Ditch on March 23. With little additional inflow after that date, specific conductance decreased slightly to near 1,600 µS/cm by the end of July. Because of the high salinity, use of this

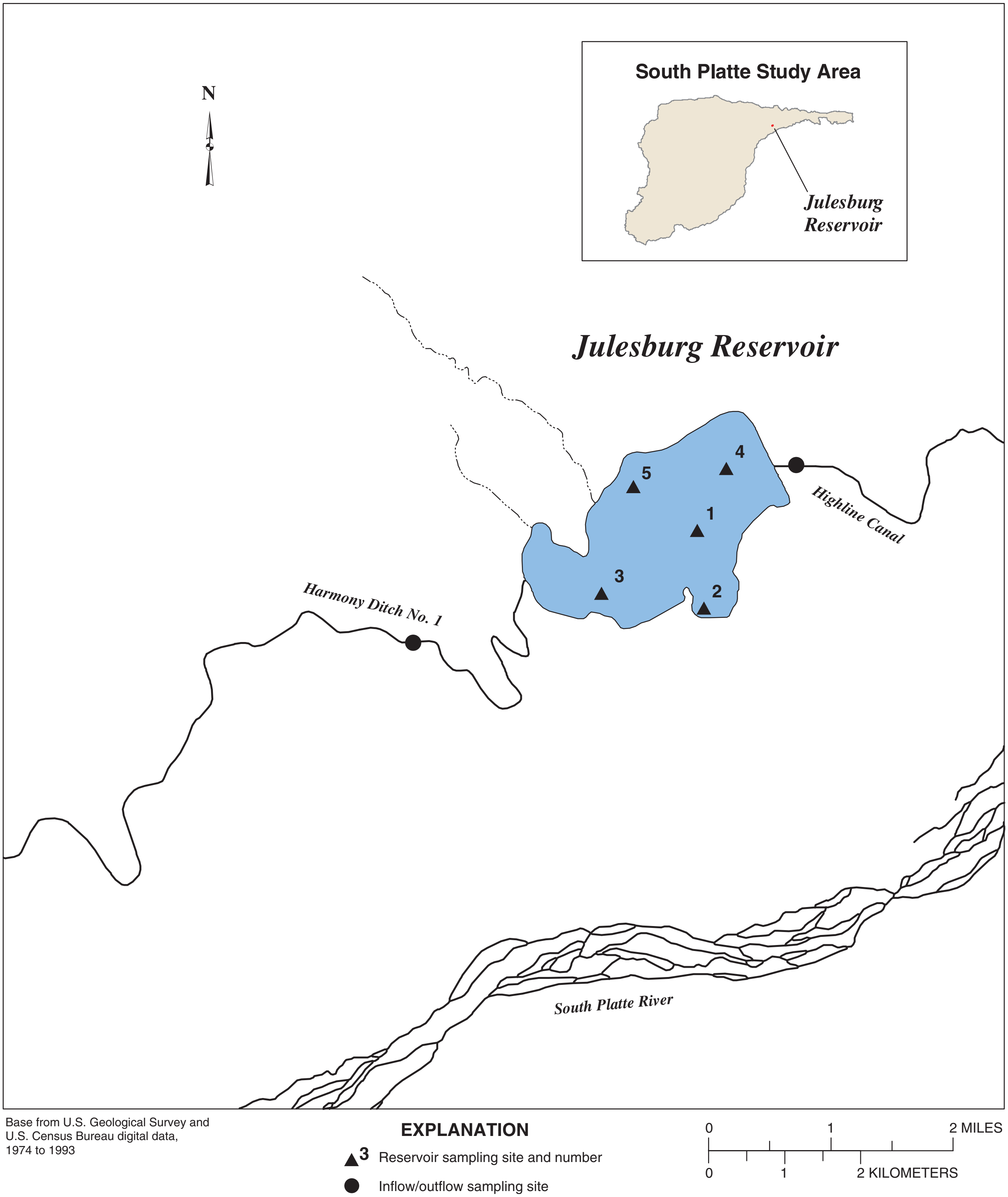


Figure 24. Location of sampling sites in Julesburg Reservoir.

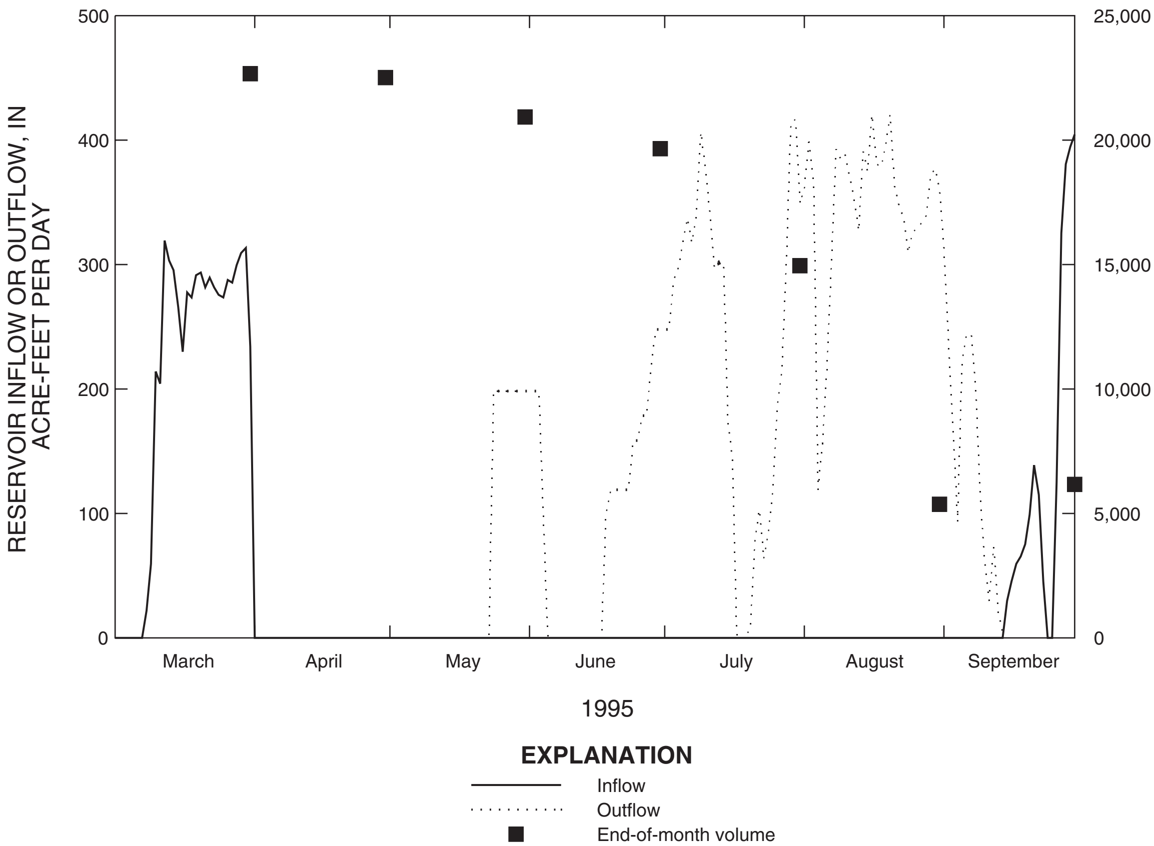


Figure 25. Inflow, outflow, and end-of-month storage volume in Julesburg Reservoir, March–September 1995.

Table 25. End-of-month storage, monthly median outflow, and residence time in Julesburg Reservoir, March–September 1995

[acre-ft, acre-feet; acre-ft/d, acre-feet per day; --, could not be calculated]

Month	End-of-month storage (acre-ft)	Monthly median outflow (acre-ft/d)	Residence time (days)
March	22,666	0	--
April	22,521	0	--
May	20,930	0	--
June	19,655	109	180
July	14,961	288	52
August	5,372	363	15
September	6,168	0	--

water for irrigation could have been detrimental to crop quality and yield (Aryes and Westcot, 1976).

Nutrient Dynamics

Water-Column Concentrations

A statistical summary of nutrient concentrations at the five sites sampled in Julesburg Reservoir, including both euphotic and bottom samples, is provided in table 26. Median concentrations of total nitrogen during the study period ranged from 1.6 mg/L at sites 3, 4, and 5 to 1.8 mg/L at site 2, and median concentrations of total phosphorus during the study period ranged from 0.020 mg/L at site 4 to 0.040 mg/L at sites 1 and 5. A statistical analysis of nutrient concentrations using the Kruskal-Wallis test indicates that the differences in nutrient concentrations between the sites were not significant (α=0.05). Because inflow

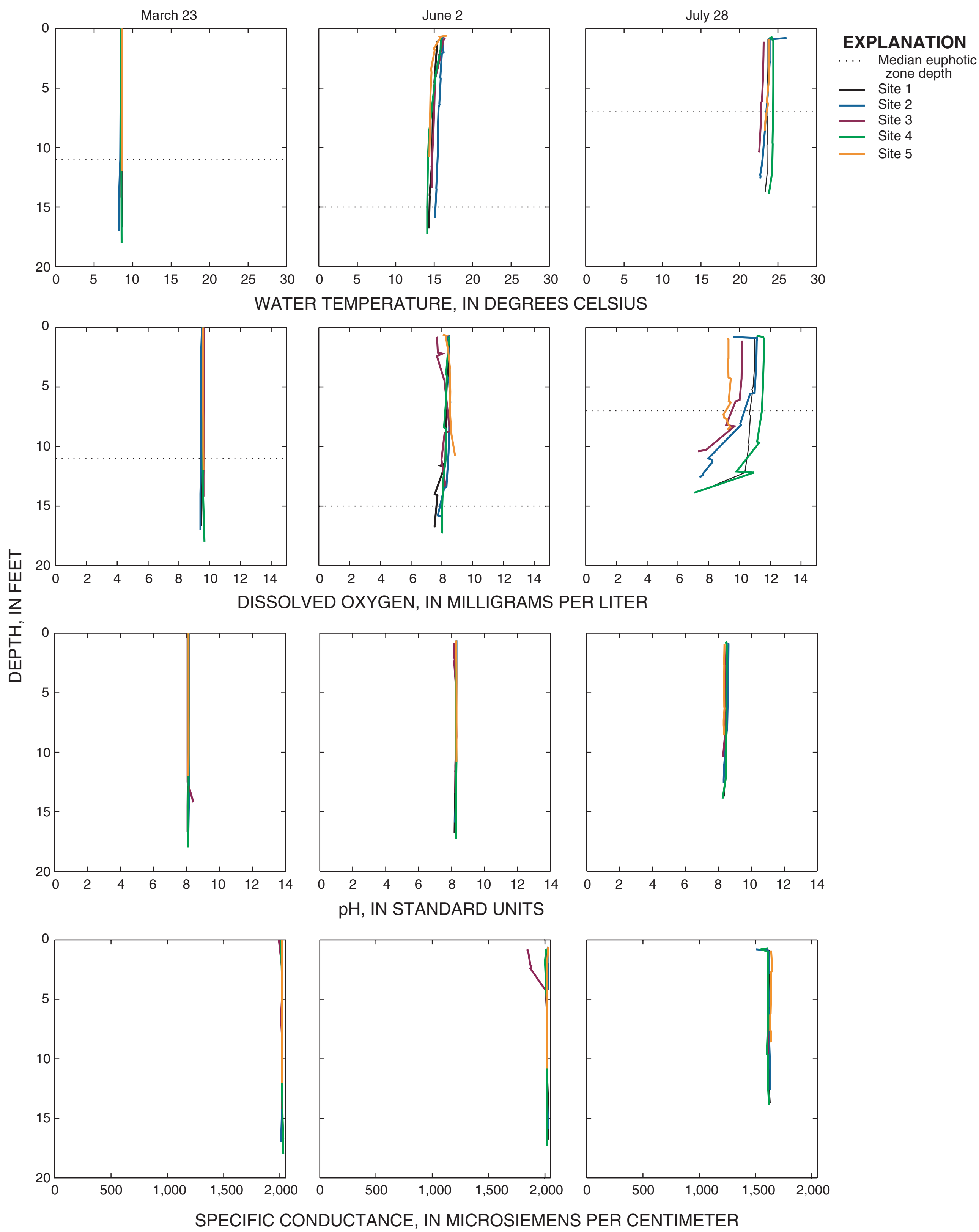


Figure 26. Depth profiles of water temperature, dissolved oxygen, pH, and specific conductance in Julesburg Reservoir, March–September 1995.

Table 26. Statistical summary of nutrient concentrations at each site and results of Kruskal-Wallis test of site concentration differences in Julesburg Reservoir, March–September 1995

[All concentrations are in milligrams per liter; p-value represents the probability that site concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Site (figure 24)	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	1	5	1.9	0.89	1.2	1.7	2.2	
	2	6	1.7	0.63	1.1	1.8	2.2	
	3	5	1.7	0.96	0.92	1.6	2.1	
	4	5	1.6	0.75	0.98	1.6	2.3	
	5	3	1.6	0.67	1.2	1.6	1.9	0.9631
Dissolved ammonia	1	5	0.10	0.064	0.030	0.14	0.15	
	2	6	0.074	0.061	0.020	0.075	0.13	
	3	5	0.070	0.073	0.015	0.020	0.15	
	4	5	0.071	0.072	0.020	0.020	0.14	
	5	3	0.12	0.058	0.10	0.15	0.15	0.3861
Dissolved nitrite	1	5	0.022	0.011	0.010	0.030	0.030	
	2	6	0.028	0.016	0.015	0.030	0.037	
	3	5	0.048	0.052	0.020	0.030	0.030	
	4	5	0.036	0.029	0.010	0.040	0.040	
	5	3	0.023	0.012	0.020	0.030	0.030	0.5679
Dissolved nitrate	1	5	0.69	0.66	0.050	0.61	1.4	
	2	6	0.64	0.67	0.095	0.39	1.2	
	3	5	0.70	0.55	0.20	0.62	1.2	
	4	5	0.50	0.53	0.070	0.42	0.60	
	5	3	0.67	0.66	0.33	0.59	0.98	0.8781
Total organic nitrogen	1	5	1.0	0.37	0.87	0.95	1.1	
	2	6	0.94	0.58	0.59	0.77	0.88	
	3	5	0.93	0.54	0.68	0.69	0.85	
	4	5	1.0	0.53	0.78	0.84	0.88	
	5	3	0.75	0.10	0.70	0.75	0.80	0.5185
Total phosphorus	1	5	0.062	0.055	0.020	0.040	0.080	
	2	6	0.042	0.050	0.013	0.025	0.037	
	3	5	0.070	0.080	0.030	0.030	0.060	
	4	5	0.056	0.070	0.020	0.020	0.040	
	5	3	0.037	0.025	0.025	0.040	0.050	0.7743
Dissolved orthophosphate	1	5	0.011	0.0045	0.010	0.010	0.010	
	2	6	0.012	0.0047	0.010	0.010	0.010	
	3	5	0.012	0.0045	0.010	0.010	0.010	
	4	5	0.011	0.0043	0.010	0.010	0.010	
	5	3	0.017	0.012	0.010	0.010	0.020	0.4380
Total organic phosphorus	1	5	0.052	0.055	0.010	0.030	0.070	
	2	6	0.032	0.050	0.0025	0.015	0.027	
	3	5	0.058	0.080	0.020	0.020	0.040	
	4	5	0.046	0.070	0.010	0.010	0.030	
	5	3	0.020	0.026	0.0050	0.010	0.030	0.6590

volumes were small and outflow volumes were substantial throughout much of the study period, residence times were short, resulting in a minimal longitudinal gradient.

Samples collected near the reservoir surface and near the reservoir bottom showed little difference between euphotic and bottom concentrations of nitrogen and phosphorus during most of the study period. Median concentrations of total phosphorus, orthophosphate, and dissolved inorganic nitrogen for all sites combined were slightly higher near the bottom during July, likely due to biological uptake in the euphotic zone. Overall, however, results of a Wilcoxon Rank-Sum test indicate that there were no statistically significant differences (α=0.05) between euphotic and bottom nutrient concentrations during the study period (table 27). The lack of variation with depth likely was because the reservoir never developed strong stratification to limit mixing between surface water and bottom water.

Although there was little longitudinal and vertical variability in nutrient concentrations, results of a Kruskal-Wallis test indicate that there was significant (α=0.05) temporal variability in total nitrogen and total phosphorus concentrations from March through September (fig. 27). Median concentrations of total nitrogen for all data combined decreased from 2.2 mg/L in March to 0.97 mg/L in July. The decrease in total nitrogen was driven largely by a decrease in nitrate; median concentrations of nitrate dropped from 1.4 mg/L in March to 0.070 mg/L in July. After reservoir inflows ceased at the end of March, continued biological activity resulted in assimilation of most of the nitrate by the end of July, and most of the

Table 27. Statistical summary of nutrient concentrations in euphotic and bottom samples and results of Wilcoxon Rank-Sum test of euphotic and bottom concentration differences in Julesburg Reservoir, March–September 1995

[e, euphotic; b, bottom; all concentrations are in milligrams per liter; p-value represents the probability that e and b concentrations have identical distributions; differences not significant at p-values greater than 0.05]

Constituent	Location	Number of analyses	Mean	Standard deviation	Twenty-fifth percentile	Median	Seventy-fifth percentile	p-value
Total nitrogen	e	18	1.7	0.67	1.1	1.7	2.2	
	b	6	1.6	0.93	0.98	1.1	1.9	0.6634
Dissolved ammonia	e	18	0.091	0.064	0.020	0.13	0.15	
	b	6	0.062	0.061	0.020	0.025	0.11	0.5649
Dissolved nitrite	e	18	0.037	0.031	0.023	0.030	0.040	
	b	6	0.018	0.0098	0.010	0.015	0.027	0.0709
Dissolved nitrate	e	18	0.67	0.54	0.17	0.60	1.3	
	b	6	0.54	0.69	0.070	0.13	1.1	0.6879
Total organic nitrogen	e	18	0.96	0.49	0.67	0.81	0.88	
	b	6	0.95	0.38	0.73	0.88	1.0	0.5480
Total phosphorus	e	18	0.052	0.060	0.020	0.025	0.040	
	b	6	0.062	0.050	0.033	0.050	0.075	0.3257
Dissolved orthophosphate	e	18	0.011	0.0047	0.010	0.010	0.010	
	b	6	0.012	0.0041	0.010	0.010	0.010	0.4870
Total organic phosphorus	e	18	0.041	0.060	0.010	0.010	0.030	
	b	6	0.050	0.050	0.023	0.035	0.063	0.2912

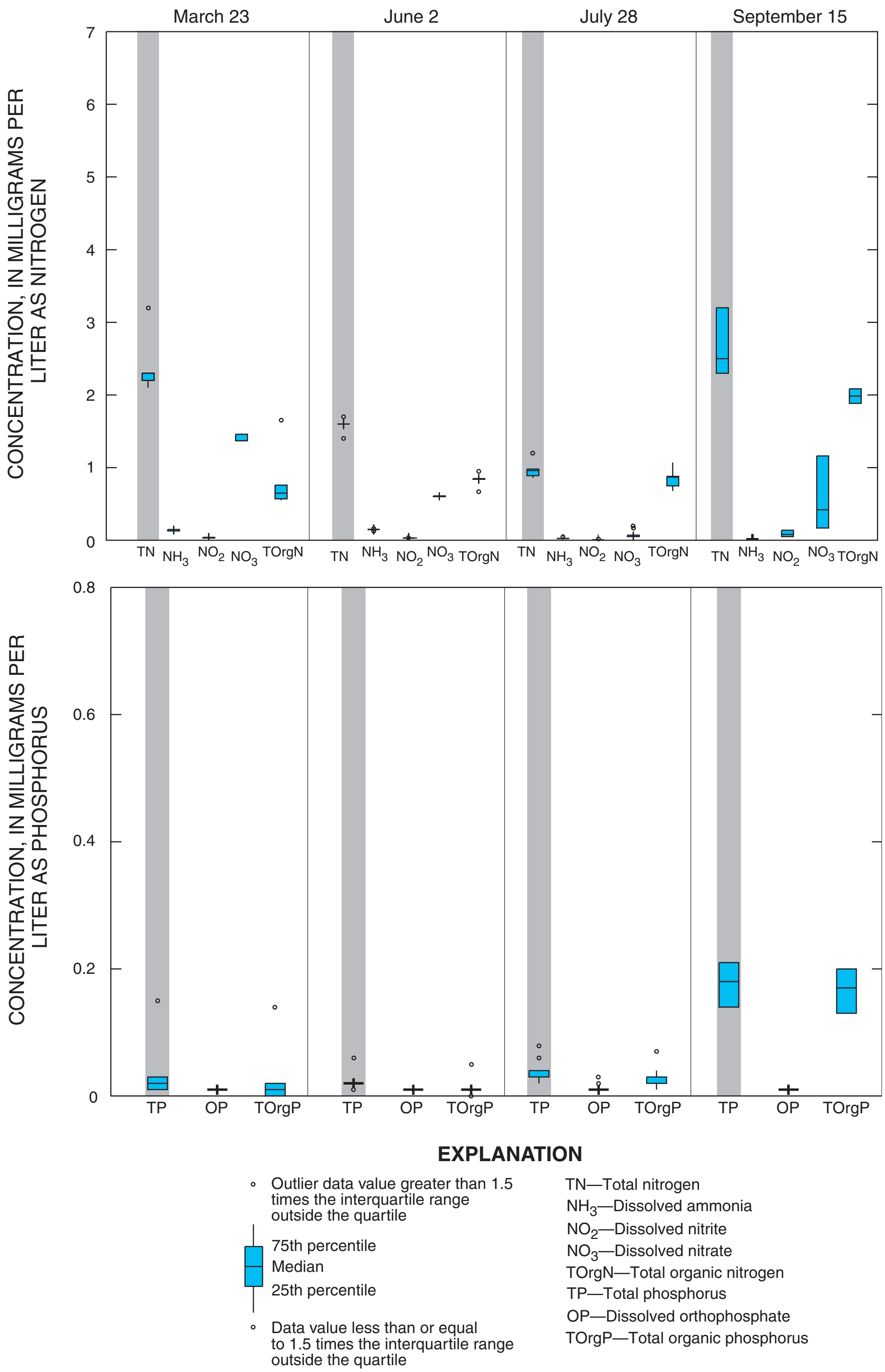


Figure 27. Nitrogen and phosphorus concentrations, euphotic and bottom samples combined in Julesburg Reservoir, March–September 1995.

remaining nitrogen was in the form of total organic nitrogen. By September, the median concentrations of total nitrogen and nitrate had increased to 2.5 and 0.42 mg/L, respectively, as inflows from the river began again. During March and September, reservoir water quality was influenced by inflowing water from the South Platte River. The influence of river water quality likely was greater in September, when inflow volumes were larger relative to the volume in storage. Concentrations of total phosphorus did not have the same consistent decrease during the study period as concentrations of total nitrogen. Median concentrations of total phosphorus for all data combined were lowest in March and June, at 0.010 mg/L, and highest in September, at 0.18 mg/L (fig. 27). The large increase in September was due to the increased inflow in the latter part of that month. Before September, internal recycling kept phosphorus levels relatively constant.

Bottom-Sediment Flux

Estimates of nutrient flux from the bottom sediment indicate that the sediment was a potential source of nutrients to the reservoir. In early spring, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were lower than in the overlying water column at site 1 but higher than in the overlying water column at site 2 (fig. 28). The estimated flux rates for inorganic nitrogen were –4.4 mg/m^2/d (into the sediment) at site 1 and 1.1 mg/m^2/d at site 2. Concentrations of dissolved

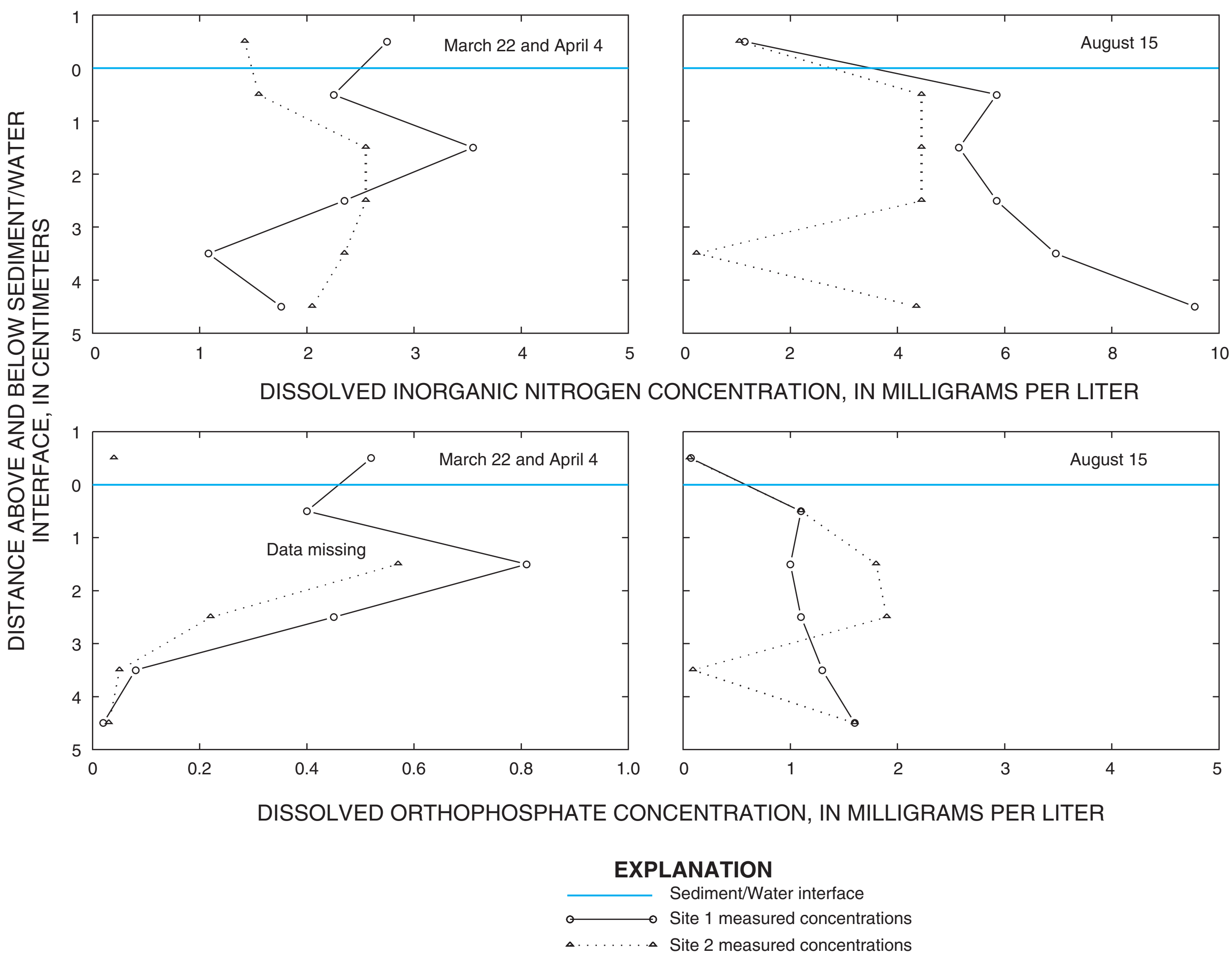


Figure 28. Concentrations of dissolved inorganic nitrogen and orthophosphate in bottom-sediment pore water and the overlying water column in Julesburg Reservoir, March 22, April 4, and August 15, 1995.

orthophosphate measured in the first centimeter of the sediment were lower than in the overlying water column at site 1 in early spring (data from –0.5 cm depth were unavailable for site 2). The estimated flux rate for orthophosphate was –0.39 mg/m^2/d (into the sediment) at site 1. In the summer, concentrations of dissolved inorganic nitrogen measured in the first centimeter of the sediment were higher than in the overlying water column at sites 1 and 2. The estimated flux rates for inorganic nitrogen were 41 mg/m^2/d at site 1 and 30 mg/m^2/d at site 2. Concentrations of dissolved orthophosphate measured in the first centimeter of the sediment also were higher than in the overlying water column at sites 1 and 2 in the summer. The estimated flux rates for orthophosphate were 3.3 mg/m^2/d at site 1 and 3.4 mg/m^2/d at site 2. The bottom dissolved oxygen concentrations at site 1 and site 2 in early spring were close to 10 mg/L, the minimum measured on March 22; concentrations on August 15 were close to 8 mg/L, the minimum measured on July 28. Because bottom sediment release is redox-dependent, movement from the sediment into the overlying water column is restricted if the sediment/water interface is well oxygenated (Horne and Goldman, 1994). Therefore, these flux calculations may overestimate the movement of nutrients between bottom sediment and the water column.

Mass Balance

Mass-balance calculations for nitrogen indicate that about 49 percent of the total mass of nitrogen—the mass that had been in storage in March plus the mass that had entered in inflows through September—was trapped in the reservoir (represented by the “unaccounted for” term), while 39 percent was released through the outflow and 13 percent remained in the water column by September (table 28). Mass-balance calculations for phosphorus indicate that about 20 percent of the total mass of phosphorus was trapped in the reservoir, while 56 percent was released through the outflow and 24 percent remained in the water

Table 28. Mass-balance calculations for total nitrogen and total phosphorus in Julesburg Reservoir, March–September 1995

[From equation 1: Unaccounted for mass = Final storage mass – Initial storage mass – Inflow mass + Outflow mass]

Date	Total nitrogen mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 8	61,254				
March 9–March 23		14,849	0		
March 24–June 2		11,046	3,916		
June 3–July 10		15,077	7,539		
July 11–August 15		10,858	20,087		
August 16– September 15		35,736	25,979		
September 15				19,028	
Total	61,254	87,566	57,520	19,028	–72,272

Date	Total phosphorus mass, in kilograms				
	Initial storage	Inflow	Outflow	Final storage	Unaccounted for
March 8	559				
March 9–March 23		144	0		
March 24–June 2		1,052	24		
June 3–July 10		1,713	411		
July 11–August 15		543	1,086		
August 16– September 15		1,642	1,636		
September 15				1,370	
Total	559	5,094	3,157	1,370	–1,126

column by September. Much of the nitrogen likely was trapped in the reservoir through biological uptake and deposition of particulate organic nitrogen onto bottom sediments (Wetzel, 1983). Much of the phosphorus likely was internally recycled due to processes such as excretion from zooplankton and fish, decay of aquatic plants and animals, and release from bottom sediment. In July and August, the reservoir had relatively short residence times and some of the recycled phosphorus still in the water column was flushed out; much of the nitrogen, however, had already been utilized by algae and was not available to be flushed out. As a result, a greater percentage of the total mass of phosphorus was released through the outflow. Overall, a substantial portion of the total nutrient mass was trapped in the reservoir during the study period and the reservoir acted as a sink for both nitrogen and phosphorus.

Algal Growth

Throughout the study period, dissolved orthophosphate concentrations generally were below the algal-growth-limiting concentration of 0.010 mg/L, indicating that phosphorus consistently was the limiting nutrient (table 29). Values of N:P also indicate that phosphorus was the limiting nutrient throughout the entire study period. In March, N:P values ranged from 70 to 220; in June, N:P values ranged from 27 to 140; in July, N:P values ranged from 4.0 to 43; and in September, N:P values ranged from 14 to 16. Because blue-green algae are less common when N:P values exceed 29, green algae likely predominated over blue-green algae until September.

Although chlorophyll-*a* measurements cannot provide information on the composition of the phytoplankton community, they can provide a measure of the quantity of algae present. Chlorophyll-*a* concentrations measured in the euphotic zone in June ranged from 0.50 µg/L at site 2 to 1.0 µg/L at sites 1 and 3 (table 30). In late July, chlorophyll-*a* concentrations ranged from 9.7 µg/L at site 3 to 17 µg/L at site 1. By September, algal biomass had increased substantially due to increased nutrient loads in inflowing water; chlorophyll-*a* concentrations ranged from 93 µg/L at site 2 to 180 µg/L at site 4. Based on mean chlorophyll-*a* concentrations, Julesburg Reservoir is classified as eutrophic. Carlson's TSI values ranged from 33 to 40 in June, from 62 to 67 in July, and from 84 to 91 in September (table 30), indicating that the algal biomass doubled approximately five times during the spring and summer. The chlorophyll, Secchi-disk, and phosphorus TSI values were similar, supporting the conclusion that phosphorus was the limiting nutrient during this period.

Table 29. Concentrations of biologically available nitrogen and phosphorus and N:P values for Julesburg Reservoir, March–September 1995

[<, less than; --, missing data; DIN, dissolved inorganic nitrogen; DOP, dissolved orthophosphate; N:P, mass ratio of nitrogen to phosphorus; values of N:P calculated from total nitrogen and total phosphorus if DIN or DOP concentrations below detection limits]

Site (figure 24)	Concentration, in milligrams per liter		N:P
	DIN	DOP	
	March 23		
1	1.5	< 0.010	110
2	1.6	< 0.010	110
3	1.5	< 0.010	70
4	1.5	< 0.010	115
5	1.5	< 0.010	220
	June 2		
1	0.8	< 0.010	85
2	0.8	< 0.010	140
3	0.8	< 0.010	80
4	0.8	< 0.010	80
5	0.8	< 0.010	27
	July 28		
1	0.090	< 0.010	24
2	0.10	< 0.010	25
3	0.21	< 0.010	30
4	0.080	< 0.010	43
5	0.12	0.03	4.0
	September 15		
1	--	--	--
2	0.23	< 0.010	16
3	1.31	< 0.010	15
4	0.51	< 0.010	14
5	--	--	--

Table 30. Chlorophyll-*a* concentrations, Secchi-disk depths, total phosphorus concentrations, and associated trophic-state indices for Julesburg Reservoir, March–September 1995

[μg/L, micrograms per liter; mg/L; milligrams per liter; TSI, Trophic State Index; Chl, chlorophyll-*a*; SD, Secchi disk; TP, total phosphorus]

Site (figure 24)	Chlorophyll-*a* concentration (μg/L)	TSI(Chl)	Secchi-disk depth (feet)	TSI(SD)	Total phosphorus concentration (mg/L)	TSI(TP)
			June 2			
1	1.0	40	7.5	48	0.020	47
2	0.50	33	7.5	48	0.010	37
3	1.0	40	6.0	51	0.020	47
			June 28			
1	17	67	4.0	57	0.040	57
2	14	65	4.0	57	0.040	57
3	9.7	62	3.0	61	0.030	53
			September 15			
2	93	84	0.75	81	0.14	75
3	150	89	0.75	81	0.21	81
4	180	91	1.0	77	0.18	79

SUMMARY AND CONCLUSIONS

In 1995, the USGS conducted a study to characterize nutrient concentrations in five off-stream reservoirs—Riverside, Jackson, Prewitt, North Sterling, and Julesburg—during the irrigation season from March through September. Water-quality data were obtained from the reservoir water column, the inflow and outflow canals, and the reservoir bottom sediment from March through September. Additional analyses of nutrient mass balances, water residence times, and chlorophyll-*a* concentrations were used to help explain nutrient dynamics in each reservoir.

The five reservoirs studied are in similar geographic, climatic, and land-use areas, and as a result, have a number of similarities in their internal nutrient dynamics. Dissolved nitrogen concentrations in the reservoirs were highest in March and decreased through September as a result of dilution from river inflows and biological activity. From March through June, decreases in nitrogen concentrations in the river contributed to corresponding decreases in reservoir concentrations. From July through September, inflows from the river were cut off, and biological activity in the reservoirs likely led to further decreases in nitrate concentrations, which fell to near or below detectable levels. Phosphorus concentrations in the reservoirs did not show the same consistent decrease from March through September. Phosphorus likely was recycled continuously back to algae during the study period through processes such as excretion from fish, decay of aquatic plants and animals, and release of orthophosphate from bottom sediment during periods of low oxygen (Wetzel, 1983). With the exception of phosphorus in Jackson Reservoir, the reservoirs acted as a sink for nitrogen and phosphorus; the percentage of the total mass (initial storage plus inflows) trapped in the reservoirs during the study period ranged from 49 to 88 percent for nitrogen and from 20 to 86 percent for phosphorus.

The nutrient loading, morphology, and operation of the five reservoirs differ, however, leading to several important differences in nutrient dynamics among the reservoirs. Approximately 95 percent of the total wastewater discharge to the South Platte River occurs upstream from Kersey, which leads to high nutrient loading into Riverside Reservoir, the closest reservoir downstream from Kersey. Mean nutrient concentrations in the reservoirs decreased in a downstream direction from Riverside Reservoir to Julesburg Reservoir as distance from the wastewater loading increased (table 31). North Sterling was an exception to this pattern. It was the deepest reservoir and therefore the most resistant to wind-induced mixing. The strong stratification and resulting anoxia that developed likely allowed for substantial internal nutrient loading from bottom-sediment releases that offset the decrease in external nutrient loading from the river. Also, North

Table 31. Comparison of morphological, operational, and nutrient characteristics of Riverside, Jackson, Prewitt, North Sterling, and Julesburg Reservoirs, March–September 1995

[mg/L, milligrams per liter; TN, total nitrogen; TP, total phosphorus; N, nitrogen; P, phosphorus; TSI, Trophic State Index; <, less than; Chl, chlorophyll-*a*]

	Riverside	Jackson	Prewitt	North Sterling	Julesburg
Mean residence time (days)	149	469	857	32	82
Maximum depth (feet)	24	18	22	54	18
Degree of summer stratification	Moderate	Weak	Weak	Strong	Weak
Date of inflow cut-off	August 8	May 31	July 15	May 29	June 4 [1]
Mean TN concentration (mg/L)	3.60	2.78	1.95	3.07	1.71
Mean TP concentration (mg/L)	0.53	0.18	0.074	0.12	0.054
Limiting nutrient	N and P	N and P	P	P	P
Percent TN mass trapped in reservoir	68	63	88	59	49
Percent TN mass lost in outflow	28	12	<1	37	39
Percent TP mass trapped in reservoir	25	+5 (gained)	86	42	20
Percent TP mass lost in outflow	65	36	<1	47	56
Median TSI(Chl)	59	72	63	72	63

[1] Inflow to Julesburg Reservoir was restarted on September 15.

Sterling Reservoir has the longest inlet canal of the five reservoirs, and agricultural runoff along its length could have contributed to increased nutrient loading in the canal between the river and the reservoir.

The variations in nutrient loading contributed to differences in the nutrient limiting algal growth in the reservoirs (table 31). In all of the reservoirs, nitrogen concentrations decreased substantially due to biological activity once inflows had ended. However, more phosphorus was internally recycled throughout the study period in Riverside and Jackson Reservoirs due to the higher initial loading of phosphorus that occurred during periods of inflow. As a result, relatively high concentrations of phosphorus were available throughout the study period in Riverside and Jackson Reservoirs, and nitrogen became the limiting nutrient by midsummer as biological activity depleted the available supply of nitrogen. Prewitt, North Sterling, and Julesburg Reservoirs, with lower initial loadings of phosphorus, were phosphorus-limited throughout the study period, with additional nitrogen limitation occurring as biological uptake reduced nitrogen concentrations to near or below laboratory detection limits.

The timing of minimum nitrogen levels in each reservoir was related to the timing of river inflows and the degree of stratification in the reservoir. In all five reservoirs, dissolved nitrogen concentrations decreased during periods of inflow as a result of dilution from river inflows and biological activity. After inflows were ended, biological activity decreased nitrate concentrations to near or below detectable levels by the next reservoir sampling date in all reservoirs except North Sterling. In North Sterling Reservoir, nutrient flux from the bottom sediment during periods of anoxia in the summer likely maintained nutrient supplies once inflows ended; after the reservoir became well mixed and well oxygenated in September, continued biological activity decreased nitrate concentrations to below detectable levels. In Julesburg Reservoir, nutrient concentrations increased once inflows began again in September, offsetting losses due to biological uptake.

The percentage of the total nitrogen and phosphorus mass (the mass that had been in storage in March plus the mass that had entered in inflows through September) lost through outflow and trapped within the reservoir due to processes such as biological uptake and sedimentation varied among the reservoirs (table 31). Generally, reservoirs with short residence times such as North Sterling and Julesburg had a higher percentage of the total mass lost through the outflow, whereas reservoirs with longer residence times like Jackson and Prewitt trapped more of the total mass within the reservoir. Riverside Reservoir, with the largest external loading of phosphorus and the greatest total outflow volume of all the reservoirs, lost the highest percentage of phosphorus in outflows. Julesburg Reservoir, which essentially acted as a flow-through reservoir (inflow = outflow) during part of the study period, lost the highest percentage of nitrogen and the second-highest percentage of phosphorus in outflows. This was probably because warmer inflowing water formed a density overflow that progressed toward the surface-level outlet with minimal mixing during periods when inflow equaled outflow.

Algal biomass generally increased throughout the study period in all five reservoirs as temperatures and light intensity increased during the summer. In Julesburg Reservoir, the late-summer influx of nutrients in inflowing river water led to a fivefold increase in chlorophyll-*a* concentrations. In Jackson Reservoir, the only reservoir without any significant inflow during the summer to replenish nutrient supplies, chlorophyll-*a* concentrations decreased sharply by September. Based on measured chlorophyll-*a* concentrations and Carlson's TSI values, all five reservoirs could be considered eutrophic by the end of the study period.

The results of this study indicate that the practice of storing South Platte River water in off-stream reservoirs substantially decreases dissolved nitrogen concentrations during the irrigation season. Associated with the decreased nitrogen concentrations, however, is an increase in algal biomass, which could adversely affect the recreational use of the reservoirs.

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APPENDIX

Appendix. Nutrient concentrations in inflow and outflow canals for Riverside, Jackson, Prewitt, North Sterling, and Julesburg Reservoirs, March–September 1995

[--, canal not flowing and could not be sampled; in months with no data shown, neither the inflow nor the outflow was flowing; Inflow1 for Prewitt Reservoir is Prewitt Inlet Canal; Inflow2 for Prewitt Reservoir is Lower Platte and Beaver Ditch; <, less than]

Date	Location	Concentration, in milligrams per liter					
		Total organic nitrogen	Dissolved ammonia	Dissolved nitrite	Dissolved nitrate	Dissolved orthophos-phate	Total organic phosphorus
				Riverside Reservoir			
May 9	Inflow	0.87	0.23	0.050	3.9	0.45	0.21
	Outflow	--	--	--	--	--	--
June 7	Inflow	0.66	0.040	0.020	0.98	0.17	0.14
	Outflow	0.91	0.29	0.15	3.1	0.49	0.020
July 12	Inflow	0.58	0.020	0.020	1.2	0.16	0.11
	Outflow	1.1	0.51	0.17	1.3	0.51	0.090
August 30	Inflow	--	--	--	--	--	--
	Outflow	1.19	0.015	0.010	0.040	0.40	0.15
September 28	Inflow	--	--	--	--	--	--
	Outflow	1.1	0.015	0.020	0.030	0.060	0.22
				Jackson Reservoir			
March 8	Inflow	0.25	0.15	0.030	4.3	0.28	0.050
	Outflow	--	--	--	--	--	--
July 12	Inflow	--	--	--	--	--	--
	Outflow	1.1	0.93	0.070	0.39	0.080	0.13
August 30	Inflow	--	--	--	--	--	--
	Outflow	1.5	0.13	0.010	0.040	0.12	0.18
September 28	Inflow	--	--	--	--	--	--
	Outflow	0.25	0.15	0.030	4.3	0.28	0.050
				Prewitt Reservoir			
March 9	Inflow1	0.38	0.020	0.030	4.0	0.17	0.030
	Inflow2	--	--	--	--	--	--
	Outflow	--	--	--	--	--	--
May 10	Inflow1	0.79	0.015	0.020	4.0	0.19	0.12
	Inflow2	1.2	0.020	0.050	4.7	0.18	0.19
	Outflow	--	--	--	--	--	--
June 6	Inflow1	0.46	0.040	0.020	1.4	0.18	0.020
	Inflow2	--	--	--	--	--	--
	Outflow	--	--	--	--	--	--
July 11	Inflow1	0.48	0.020	0.010	1.6	0.15	0.030
	Inflow2	0.17	0.030	0.020	2.0	0.14	0.57
	Outflow	--	--	--	--	--	--
August 17	Inflow1	--	--	--	--	--	--
	Inflow2	1.2	0.13	0.030	0.59	0.10	0.26
	Outflow	1.1	0.11	0.010	0.040	0.010	0.070
September 13	Inflow1	--	--	--	--	--	--
	Inflow2	1.6	0.015	0.020	3.1	0.020	0.070

Appendix. Nutrient concentrations in inflow and outflow canals for Riverside, Jackson, Prewitt, North Sterling, and Julesburg Reservoirs, March–September 1995—Continued

[--, canal not flowing and could not be sampled; in months with no data shown, neither the inflow nor the outflow was flowing; Inflow1 for Prewitt Reservoir is Prewitt Inlet Canal; Inflow2 for Prewitt Reservoir is Lower Platte and Beaver Ditch; <, less than]

Date	Location	Concentration, in milligrams per liter					
		Total organic nitrogen	Dissolved ammonia	Dissolved nitrite	Dissolved nitrate	Dissolved orthophosphate	Total organic phosphorus
North Sterling Reservoir							
March 10	Inflow	0.88	0.020	0.050	6.1	0.25	0.24
	Outflow	--	--	--	--	--	--
May 11	Inflow	1.4	0.015	0.020	4.1	0.22	0.28
	Outflow	0.81	0.090	0.050	2.3	0.010	0.050
July 11	Inflow	--	--	--	--	--	--
	Outflow	0.75	0.45	0.090	1.3	0.050	0.020
August 16	Inflow	--	--	--	--	--	--
	Outflow	1.1	0.30	0.060	0.17	0.040	0.050
September 14	Inflow	--	--	--	--	--	--
	Outflow	1.1	0.36	0.010	0.040	0.010	0.10
Julesburg Reservoir							
March 23	Inflow	0.39	0.015	0.030	2.7	0.030	< 0.010
	Outflow	--	--	--	--	--	--
June 2	Inflow	0.96	0.14	0.030	0.97	0.16	0.040
	Outflow	0.84	0.16	0.040	0.61	0.010	< 0.010
July 10	Inflow	0.71	0.090	0.030	1.4	0.15	0.10
	Outflow	0.85	0.050	0.030	0.13	0.010	0.050
August 15	Inflow	0.56	0.14	0.030	0.29	0.010	0.040
	Outflow	1.6	0.20	0.010	0.040	0.010	0.090
September 15	Inflow	0.99	0.015	0.020	2.7	0.040	0.13
	Outflow	2.3	0.015	0.070	0.30	0.010	0.16