APPLICABILITY OF TROPHIC STATUS INDICATORS TO COLORADO PLAINS RESERVOIRS

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John D. Stednick and Emile B. Hall

Colorado Water
Resources Research Institute

Completion Report No. 195

Colorado State University

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Abstract

Off channel storage reservoirs along the South Platte River downstream of Denver, Colorado are often filled with river water that may contain high concentrations of nitrogen and phosphorous. This study measured reservoir nutrient concentrations from April through October 2001 in Jackson, Prewitt and North Sterling Reservoirs. Median total nitrogen (TN) concentrations in Jackson (2,550 μg/L), Prewitt (3,100 μg/L) and North Sterling (3,550 μg/L) reservoirs exceed the EPA standard recommendation of 560 μg/L. Median total phosphorous (TP) concentrations in Jackson (208 μg/L), Prewitt (267 μg/L) and North Sterling (183 μg/L) exceeded the EPA recommendation of 33 μg/L. Median chlorophyll-*a* concentrations exceeded the recommended value of 2.33 μg/L by a factor of at least 20.

Linear and multiple regression were used to determine the relationships between nutrient concentrations and chlorophyll-*a*. TP and chlorophyll-*a* were positively correlated (α=0.10) at North Sterling (r^2=0.53; p=0.04) and Jackson Reservoirs (r^2=0.59; p=0.03), but not at Prewitt Reservoir (r^2=0.27; p=0.19). Multivariate regression using TN and TP strengthened the correlation with chlorophyll-*a* at all of the reservoirs. Multivariate regression using inorganic-N and TP resulted in the strongest correlation at North Sterling Reservoir.

An analysis of the applicability of common Trophic Status Index (TSI) models suggested that all reservoirs are eutrophic - hypereutrophic based upon chlorophyll-*a*, TP and Secchi depth measurements. Models using chlorophyll-*a* generally resulted in a lower trophic designation than those based upon TP. Model precision analysis (correlation coefficients, 95% confidence intervals, and average and percentage error) was used to evaluate 24 common models that predict chlorophyll-*a* from nutrient concentrations. Using precision analysis, models based upon TP were the best at Prewitt Reservoir, while models using TN and TP were best at Jackson and Sterling Reservoirs. This study suggested that one model does not fit all reservoirs. Based on precision analysis and model selection methods, nitrogen and phosphorous concentrations should be used when assessing off channel storage reservoir trophic status.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Anecdotal evidence indicates that off-channel storage reservoirs on the eastern Colorado plains downstream of Denver, Colorado are experiencing symptoms of eutrophication. Algae blooms and fish kills occur in some storage reservoirs. Eutrophication in off-channel storage reservoirs may impair the recreational and aquatic life beneficial uses. This project examines the in-reservoir nitrogen and phosphorous concentrations in relation to the reservoir response, as measured by chlorophyll-*a*. The determination of the nutrient ~ chlorophyll-*a* relationships will aid in evaluating off-channel reservoir trophic status, predicting future eutrophication potential, and identifying reservoir management options.

From Denver to Balzac Colorado, total phosphorous (TP) concentrations in the main stem of the South Platte River generally exceed the U.S. Environmental Protection Agency (EPA) recommendation of less than 67.5 μg/L (USGS 1998, Hernandez 2002). One study of the South Platte River in 1995 found TP concentrations greater than 2,000 μg/L immediately downstream of Denver, with concentrations decreasing to approximately 500 μg/L near Balzac (Litke 1996). Off channel storage reservoirs in the South Platte River region downstream of Denver are filled with this high nutrient level water (USGS 1998). The primary purpose of the off channel storage reservoirs is to provide irrigation water. Many of the reservoirs are also operated as State Parks or wildlife areas and provide recreational opportunities leading to increased public pressure for stable water levels and good water quality (Maurier 2001).

High nutrient concentrations in aquatic ecosystems can result in increased primary production. The process of eutrophication encompasses both the addition of nutrients to aquatic environments and the effects of those nutrients on reservoir water quality and primary production. Trophic state terminology (ultraoligotrophic, oligotrophic, mesotrophic, eutrophic, hypereutrophic) and trophic status indices (TSI) describe the level of eutrophication with hypereutrophic being the most advanced stage of nutrient inputs and water quality affects. According to Carlson's TSI the reservoirs are classified as eutrophic or hypereutrophic based upon prior chlorophyll-*a* and TP measurements (Carlson 1977).

Reservoir nutrients and water quality

Bioavailable nutrients, or nutrients in a readily usable form, are generally thought to control primary production, or organic matter production, in lakes and reservoirs, although many other factors contribute to primary production (Novotny and Olem 1994) such as light, temperature, and micronutrients. Reservoir primary production is typically measured by chlorophyll-*a* concentrations and is affected by light and temperature along with nutrient concentrations (Chapra 1997). The modern definition of eutrophication includes not only an increase in nutrient concentrations, but also the effects of additional nutrients on water quality and biota. The definition of eutrophication adopted by the Organization for Economic Co-Operation and Development (OECD) is the nutrient enrichment of waters that results in the stimulation of an array of symptomatic changes, including increased production of algae and macrophytes, and deterioration of water quality (OECD 1982). These symptomatic changes are found to be undesirable and may interfere with beneficial uses.

The level of eutrophication can be classified by the trophic state index. Ultraoligotrophic lakes have low nutrient concentrations, low algae growth and high transparency. As nutrient concentrations and primary production increase, the water body classification can change from ultraoligotrophic to oligotrophic, mesotrophic, eutrophic and finally, hypereutrophic. An increase in TP can be responsible for a shift in these trophic designations because TP is typically limiting in aquatic environments. Consequently, most TSI rely upon phosphorous concentrations to define trophic classification. Transparency (measured by Secchi depth), nitrogen and chlorophyll-*a* concentrations are also used in estimating trophic status (Novotny and Olem 1994). Some characteristics of each follow.

In aquatic environments phosphorous is typically the nutrient in shortest supply (Novotny and Olem 1994) relative to nitrogen for several reasons. The atmosphere is not a source of phosphorous because phosphorous does not exist in gaseous phase as nitrogen does. Also, the phosphate in the Earth's crust is not very water soluble. Phosphorous sorbs strongly to soil particles making erosion and dry deposition one source of phosphorous in water. Sorption to soil particles also allows it to be removed by sedimentation (Chapra 1997). The typical TP concentration in lake surface water is 10 - 40 μg/L as phosphorous (Snoeyink and Jenkins 1980). Although phosphorous is naturally scarce, human activities can increase phosphorous in waters through human and animal waste, detergents and fertilizers, and erosion (Chapra 1997).

Nitrogen is more abundant than phosphorous and therefore less limiting to aquatic primary productivity (Chapra 1997). However, nitrogen in both bioavailable and total concentrations is still used in predicting eutrophication. Bioavailable (or inorganic-N) nitrogen is the summation of ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). Total nitrogen (TN) is the summation of Total Kjeldahl Nitrogen (TKN), nitrate and nitrite. Nitrogen differs from phosphorous in that it does not readily sorb to soil particles, it exists in the atmosphere and may be removed from the aquatic ecosystem through denitrification (Chapra 1997).

Nitrogen:Phosphorous (N:P) ratios are useful in defining the nutrient in shortest supply that will limit algal growth (Chapra 1997). Most surface waters are nitrogen or phosphorous limited, however, they may be carbon limited (Novotny and Olem 1994). The use of N:P ratios to assess nutrient limitation assumes that algal growth is proportional to the quantity of either nitrogen or phosphorous in the water body (Ryding and Rast 1989). While this may not always be the case, total and bioavailable N:P ratios can provide useful information regarding nutrient limitation. Traditionally, a mass nutrient ratio of 7.2 or less indicates nitrogen limitation and a ratio of greater than 7.2 indicates phosphorous limitation. Nutrient ratios should not be applied too strictly.

Nutrient ratio variations to account for regional differences and an interval where both nutrients may be limiting have been used. Ratios less than 10 indicated nitrogen limitation, ratios between 10 and 17 indicated co-limitation, and ratios greater than 17 showed phosphorous limitation (Ryding and Rast 1989). Ratios of both total and bioavailable forms of the nutrients should be computed (Ryding and Rast 1989). A ratio can be computed even when nutrients are present in sufficient quantities and production is limited by light, temperature or another factor. Thus, nutrient ratio computation should be used along with nutrient concentration information when assessing the potential limiting nutrient. Nutrient levels are the causative factors and transparency and chlorophyll-*a* are the response factors measured to evaluate eutrophication (Hernandez 2002).

The use of transparency (as measured by Secchi disk) to estimate chlorophyll has been criticized because of sources of error in the measurement, specifically the light attenuating effects of substances other than algae (Lorenzen 1980, Megard et al. 1980). Highly turbid water will result in shallow Secchi depth measurements, possibly due to substances other than algae. Occasionally, when the phytoplankton population is dominated by large colonies of *Anabena* or *Aphanizomenon* that form aggregations, deep Secchi disk values are associated with relatively high chlorophyll values (Edmondson 1980). Although the sources of error in relating Secchi disk depth with algal biomass have been identified, this measure is still commonly used.

Chlorophyll-*a*, another response variable, is used to assess the trophic status of a lake by estimating phytoplankton biomass. Algae, plants and cyanobacteria contain chlorophyll-*a*, a photosynthetic pigment that typically constitutes 1 - 2 % of the dry weight of planktonic algae (APHA 1995). The chlorophyll content of algae varies depending upon light availability, temperature and metabolism (Wetzel and Likens 2000). Hypereutrophic lakes and reservoirs can have chlorophyll-*a* concentrations greater than 200 μg/L (Novotny and Olem 1994). One of the most important response factors of eutrophication is the accumulation of nuisance levels of algal biomass (Smith and Bennett 1999), making chlorophyll-*a* measurements important in eutrophication evaluation.

Along with nutrient, transparency and algal biomass changes, advanced eutrophication can cause pH and dissolved oxygen variation. These variations may interfere with recreational, aesthetic and fishery water usage. In addition, problems associated with algae can make the water less suitable for potable use and contact recreation (Novotny and Olem 1994).

Trophic Status Indices and Models

Lake habitat classification schemes have been based upon geography, physical factors, chemical factors, aquatic species and trophic status. Of the many options, trophic classification is currently the most widely used and accepted (Leach and Herron 1992). The traditional classification of lakes and reservoirs divides them into three categories: oligotrophic, mesotrophic and eutrophic. This categorical delineation is inadequate for most purposes since it reduces large variability in lakes and reservoirs to only three designations (Shapiro 1979). This spurred the development of many indices and methods to describe lakes and reservoirs. A single parameter or a composite of parameters can define trophic status. Typical parameters are dissolved oxygen, primary production, TP, TN, chlorophyll-*a*, transparency and organic matter in sediments (Leach and Herron 1992). Several of these parameters are combined to develop composite indices.

The relationship between nutrient concentrations and algal biomass has long been recognized and is the basis for many commonly used eutrophication models (Brown et al. 2000). The general assumption for these equations is that as TP increases, chlorophyll-*a* will increase because phosphorous is the nutrient controlling alga growth. In some systems, nitrogen is the limiting nutrient and several models incorporate both TN and TP (Hoyer 1981, Smith 1982, Canfield et al. 1983, Canfield Jr. 1983, Brown et al. 2000). Over the past thirty years, many popular classification systems have evolved from the need to compare the trophic state of reservoirs in order to describe the present and future trophic condition in a clear manner. The following section describes several models.

Examples of model
s

Carlson Trophic Index

The Carson Index was developed for phosphorous limited lakes and reservoirs (Carlson 1977). This index relies on the interrelation between Secchi depth, chlorophyll-*a* concentrations and average annual phosphorous (Table 1). Index values and corresponding TP, chlorophyll-*a* and transparency are shown graphically (Figure 1). The Carlson Index was used to evaluate the trophic state of Arvada Reservoir using all three indicator variables (USGS 1987).

U.S. EPA National Eutrophication Survey

The EPA developed a relative classification system as part of the National Eutrophication Survey (EPA 1974). The system used parameters measured from a group of lakes and reservoirs in order to classify them relative to one another. The system determined the fixed boundaries listed in Table 1. Data collected during the national eutrophication survey were later used to develop a probability distribution based upon TP to predict chlorophyll-*a* and transparency probabilities (Figure 2).

Vollenweider

Vollenweider devised a model based upon a phosphorous loading concept (Vollenweider 1975) Both depth (H) and residence time (τ_w) are considered in relation to the loading of TP (Lp) (g/m^2/yr). The depth is defined as the mean reservoir depth and the residence time is the reservoir volume divided by the total annual outflow. The total annual input of TP is divided by reservoir surface area to determine Lp. A loading plot is

Table 1: Trophic Status Indices

<table>
<tr><th>Index</th><th></th><th>Reference</th></tr>
<tr><td>Carlson Trophic Status Index</td><td>An index that uses TP, transparency and chlorophyll-*a* to define the trophic status as a numerical value from 0 to approximately 100.

$TSI\ (SD) = 10(6 - \ln SD/\ln 2)$
$TSI\ (chl) = 10(6-(2.04-0.68 \ln chl)/\ln 2)$
$TSI\ (TP) = 10(6 - (48/TP) / \ln 2)$

See Figure 1</td><td>(Carlson 1977)</td></tr>
<tr><td>National Eutrophication Survey</td><td>Fixed boundaries based upon the results of the National Eutrophication Survey:<table><tr><th></th><th>Chl</th><th>TP</th><th>SD</th></tr><tr><td>Oligotrophic</td><td>< 7</td><td>< 10</td><td>> 3.7</td></tr><tr><td>Mesotrophic</td><td>7 - 12</td><td>10 - 20</td><td>3.7 - 2</td></tr><tr><td>Eutrophic</td><td>> 12</td><td>> 20</td><td>< 2</td></tr></table></td><td>(EPA 1974)</td></tr>
<tr><td>U.S. Environmental Protection Agency</td><td>A probability classification system based upon NES data using TP concentrations in intervals to predict mean chlorophyll-*a* and Secchi disk depth.
See Figure 2</td><td>(EPA 1988)</td></tr>
<tr><td>Loading Plots</td><td>Trophic classification based upon plots of phosphorous loading and mean depth-hydraulic residence time. (See Figure 3) Also provides an average inflow concentration and residence time plot.</td><td>(Vollenweider 1976)</td></tr>
<tr><td>Trophic State Classification Probabilities</td><td>Plots using average lake TP and average lake chlorophyll-*a* to determine the trophic status probabilities.
See Figure 4</td><td>(OECD 1982)</td></tr>
<tr><td>OECD Fixed Boundary System</td><td>Uses the mean chlorophyll-*a*, total phosphorous and Secchi depth, along with the peak chlorophyll-*a* and the minimum Secchi depth to classify a lake or reservoir from ultraoligotrophic to hypereutrophic.
See Table 2</td><td>(OECD 1982)</td></tr>
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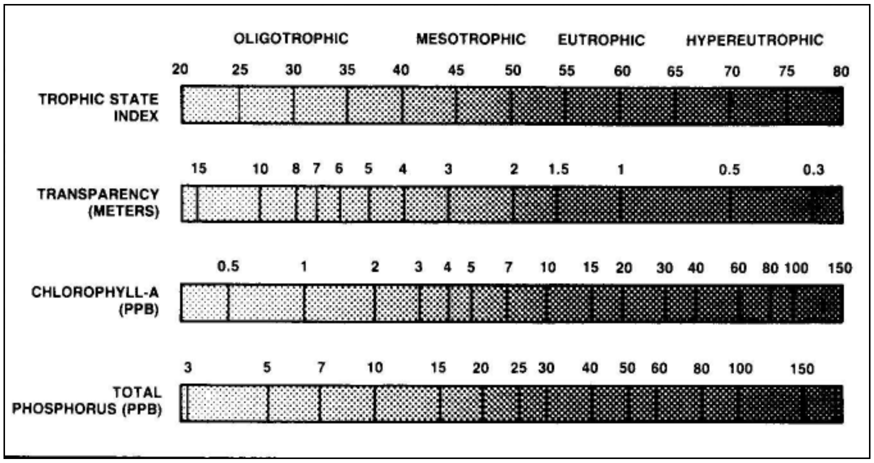

Figure 1. Carlson's Trophic Status Index related to transparency, chlorophyll-*a* and TP (Adapted from EPA, 1988).

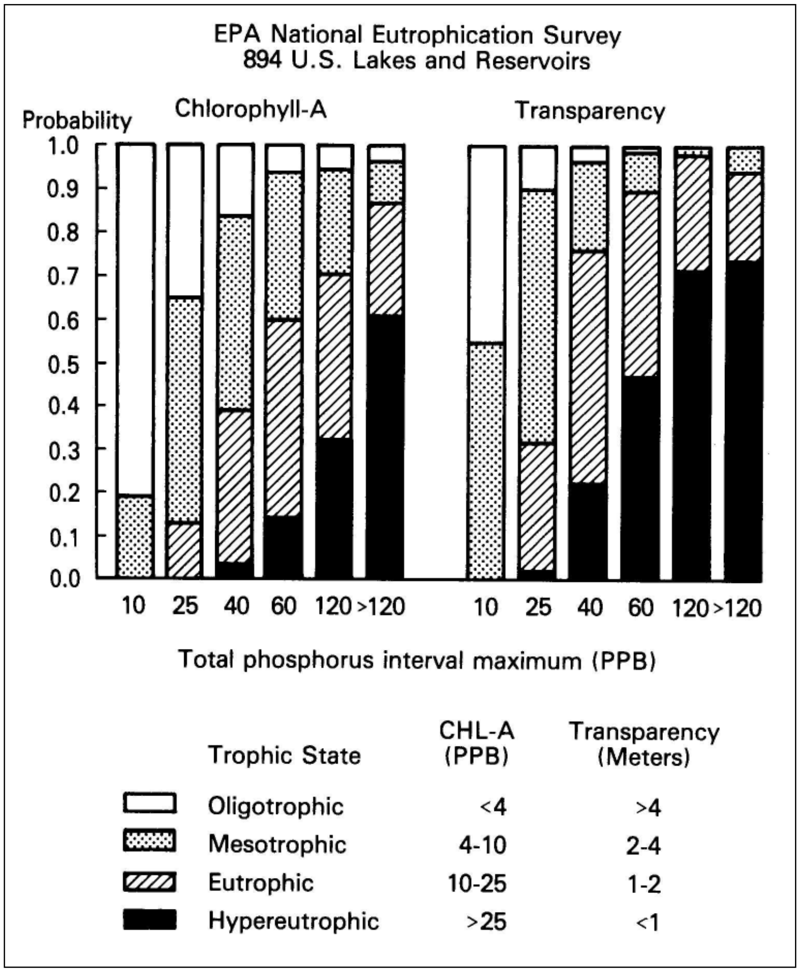

Figure 2. Probability responses of mean chlorophyll-*a* and transparency to TP concentrations (EPA 1988).

then used to evaluate the trophic status. The dashed lines represent the original model while the curved lines represent a superior fit to the data (Chapra 1997); (Figure 3).

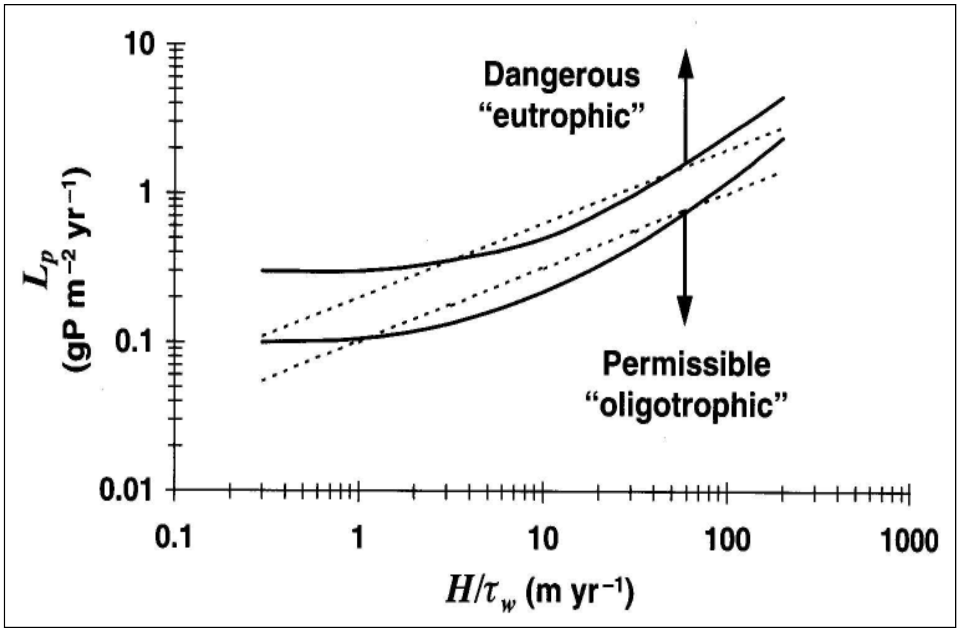

Figure 3: Vollenweider's 1975 loading plot (adapted by Chapra, 1997).

OECD Probability Curve

Vollenweider proposed another classification scheme based upon probabilities and chlorophyll-*a* concentration during the OECD program on eutrophication (OECD 1982). Average chlorophyll-*a* or TP, measured during the growing season, are used to determine the most likely trophic classification for the lake and the probability that the lake will be within a particular classification is taken from the probability curves. The Cherry Creek Reservoir Clean Lakes Study (1984) used the probability curve method in designating Cherry Creek Reservoir as eutrophic (DRCOG 1984); (Figure 4).

OECD Fixed Boundary System

This fixed system defines boundaries for mean phosphorous, chlorophyll-*a* and Secchi depth (Table 2). It is characterized by ease of use and all parameters should be used when classifying a water body. Locally, this system resulted in three different classifications of the same reservoir; Arvada Reservoir was found to be oligotrophic (TP), mesotrophic (chlorophyll-*a*) and eutrophic (Secchi disk depth) (USGS 1987).

To define trophic status, TSI rely upon the relationship between control and response variables, typically TP and chlorophyll-*a*. A local example of the implementation of a TP~chlorophyll-*a* model for future prediction comes from the Chatfield Basin Water Quality Study (DRCOG 1988). The study used a derivation of the Vollenweider model to predict TP concentrations in Chatfield Reservoir (Canfield and Bachmann 1980).

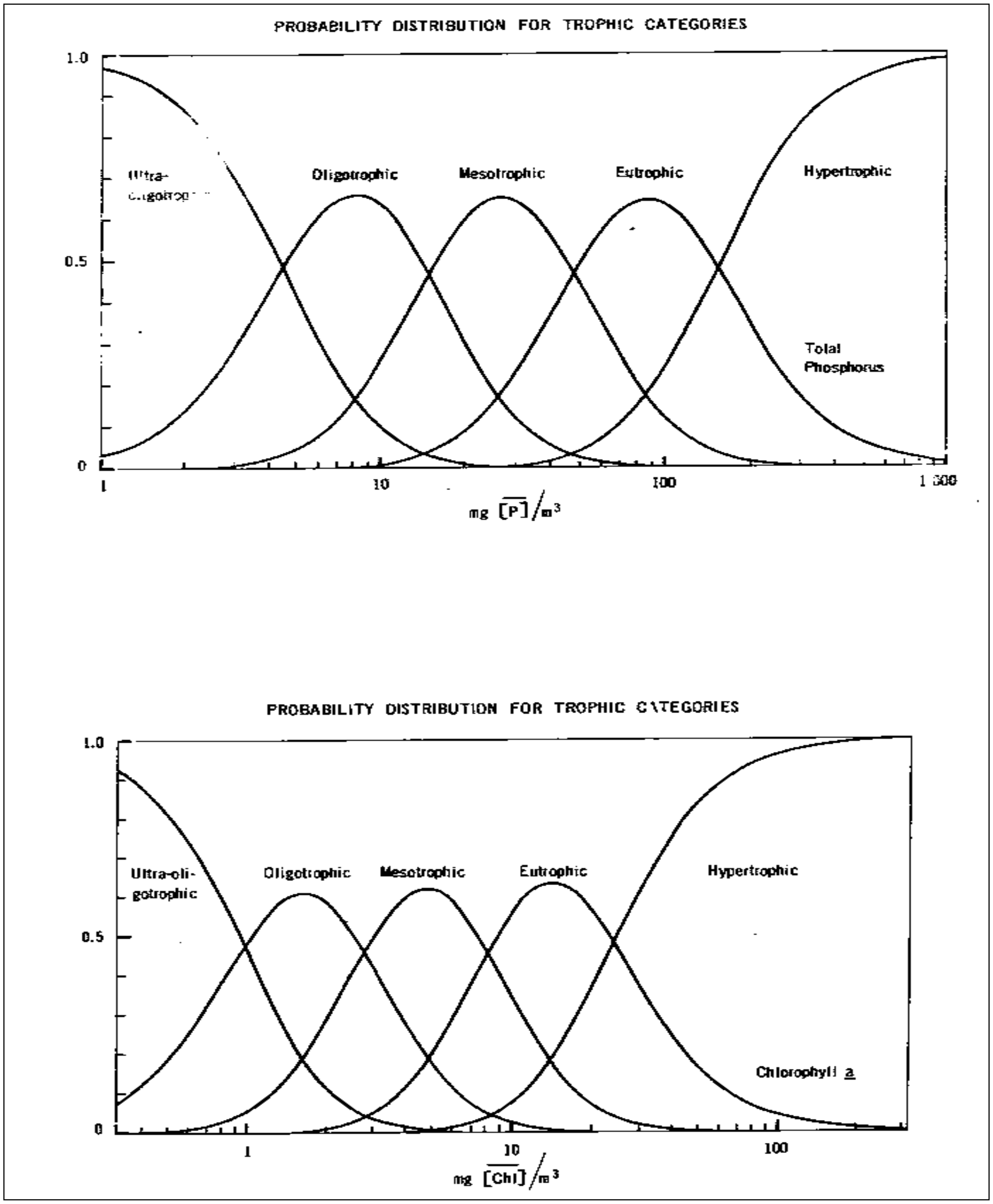

Figure 4: OECD Trophic State Classification Probabilities

Predicted TP concentrations were then used to estimate chlorophyll-*a* concentrations using an equation developed by Jones and Bachmann (1976):

$$\log \text{chlorophyll-}a = -0.85 + 1.46 \log \text{TP}$$

Table 2: OECD Fixed Boundary System (OECD, 1982)

	Annual mean TP	Annual mean chlorophyll-*a*	Annual peak chlorophyll-*a*	Annual mean Secchi disk depth	Annual minimum Secchi disk depth
	μg/L			M	
Ultra-oligotrophic	≤ 4.0	≤ 1.0	≤ 2.5	≥ 12.0	≥ 6.0
Oligotrophic	≤10.0	≤ 2.5	≤ 8.0	≥ 6.0	≥ 3.0
Mesotrophic	10-35	2.5 - 8	8 – 25	6 - 3	3 - 1.5
Eutrophic	35-100	8 - 25	25 – 75	3-1.5	1.5 - 0.7
Hyper-Eutrophic	≥ 100	≥ 25	≥ 75	≤ 1.5	≤ 0.7

Both models, one predicting TP and the other predicting chlorophyll-*a* (above), were adjusted for local conditions by altering the sedimentation coefficient and the y-intercept. Even though the model was modified, the data from 1983 until the publication of the study in 1988 showed summer average phosphorous levels above the 27 μg/L standard, however, the 17 μg/L chlorophyll-*a* goal was not exceeded. (DRCOG 1988). Thus, the model predictions of chlorophyll-*a* based upon TP concentration did not reflect the true chlorophyll-*a* concentrations at Chatfield Reservoir. As evidenced by this situation, determining a suitable nutrient~chlorophyll-*a* model for a particular region may be challenging. The ultimate goal of describing such a relationship is reservoir classification to facilitate planning and management. The utility of the TP~chlorophyll-*a* relationship needs to be improved by a more accurate model, site specific models or an alternate method to describe the system and aid in reservoir management.

The relationship between phosphorous and chlorophyll-*a* has long been the subject of scientific studies. During the past 40 years, researchers have used this relationship to develop equations to predict chlorophyll-*a* concentrations from phosphorous measurements (Sakamoto 1966, Dillon and Ringer 1974, Jones and Bachmann 1976, Carlson 1977, Canfield and Bachmann 1980, Baker et al. 1981, Hoyer 1981, Huber et al. 1982, Canfield et al. 1983, Brezonik 1984, Reckhow 1988, Brown et al. 2000). The relationships have been determined for different geographical regions and conditions. The determination of a multitude of equations may be due to the sigmoidal relationship between TP and chlorophyll-*a* observed by many researchers (Brown et al. 2000).

South Platte Basin Plains Reservoirs

The South Platte River downstream of Denver, Colorado often is dominated by effluent from wastewater treatment plants (Litke 1996), and the wastewater flow contributes to elevated nutrient concentrations in the South Platte River. The Metro Wastewater Reclamation District contributes 69% of the annual flow in the river (Litke

1996). The annual estimate of nutrient inputs into the South Platte Basin states that wastewater treatment plants contribute 6,350,000 kilograms of nitrogen per year and 1,088,000 kilograms of phosphorous per year (Litke 1996). Nutrient load estimates show that the South Platte River is effluent dominated for ninety-five kilometers downstream of Denver. Other sources of nutrients along the South Platte River include nonpoint source inputs from urban runoff, atmospheric inputs and agricultural return flows to the river. Increased nutrients in the river can lead to eutrophication, especially in reservoirs.

The National Water Quality Assessment (NAWQA) program conducted a study of nutrient concentrations in five South Platte reservoirs in 1995 (USGS 1998). A preliminary analysis of the data shows that the reservoirs are eutrophic with TP concentrations in all of the reservoirs frequently exceeding 20 μg/L (USGS 1995b). Elevated nitrate concentrations early in the spring (soon after reservoir filling) decrease over the season. This finding led to the suggestion that the reservoirs could be part of a nitrate mitigation strategy (USGS, 1998).

Other than four sampling days in 1995, no nutrient studies on Jackson, Prewitt and North Sterling Reservoirs were found. No alga studies on the reservoirs were found, and there is little information on algae in the plains region of the South Platte Basin (USGS 1995a).

Although little nutrient or algae information was found, a warm water classification system for Colorado reservoirs was developed with respect to sport fishing over forty years ago by the Colorado Department of Game, Fish and Parks (Lynch 1963). The system uses the condition of the reservoir pool during low reservoir volume, freshwater inflow and average amount of water maintained in storage to determine guidelines for fish habitat. North Sterling and Jackson Reservoir were classified as highly important for recreational investment with permanent conservation pools and good freshwater inflows. Prewitt Reservoir is classified as having a highly productive fishery, but lacking an adequate conservation pool. This results in entire fish population loss once or twice every fifteen years (Lynch 1963).

The EPA recently developed nutrient criteria and guidance for the South Platte River Basin (EPA 2001). Recommendations for nutrient levels for rivers and reservoirs of the South Platte Basin in Ecoregion V (South Central Cultivated Great Plains) exist (Table 3). The criteria are intended to aid the State in developing nutrient standards. At the November 2000 rule making hearing for the South Platte Basin, the Colorado Water Quality Control Commission recognized the need for an effort to address South Platte Reservoir eutrophication and suggested a study to advance the understanding of these systems (CDPHE 2002). The elevated nutrient concentrations, lack of previous reservoir studies, and pending state nutrient criteria recommendations in South Platte

Table 3: EPA causative and response numeric values for Ecoregion V (EPA 2001)

Parameter	Rivers and Streams	Lakes and Reservoirs
TP	67.5 μg/L	33 μg/L
TN	0.88 mg/L	0.56 mg/L
Chlorophyll-*a*	3.04 μg/L	2.3 μg/L
Turbidity or Transparency	8 NTU	1.3 meters

River reservoirs prompted this study. This thesis addresses the need for off channel storage reservoir information by characterizing portions of the Eastern Colorado reservoir system. This information is needed to establish TSI or other trophic status prediction tools that will aid in reservoir management. This thesis examined three reservoirs along the South Platte River in order to describe the nutrient~chlorophyll-*a* relationship, to determine the limiting nutrient, to identify some of the existing phytoplankton, and to evaluate the use of common TSI in reservoir management.

Hypothesis and Objectives

This research examined nutrients and primary production in three off channel storage reservoirs: Jackson Reservoir, Prewitt Reservoir and North Sterling Reservoir. Seasonal in-reservoir nutrient concentrations will be examined and applied to a discussion of nutrient limitation, trophic status and algae growth.

Hypothesis: In waters of off-channel reservoirs along the South Platte River in eastern Colorado, TN and TP concentrations are positively correlated with primary production.
Objectives:

1. To measure nutrient concentrations and identify trends in Jackson Reservoir, Prewitt Reservoir and North Sterling Reservoir.
2.
3. To determine the relationship between phosphorous and chlorophyll-*a* and the nitrogen~chlorophyll-*a* relationship in Jackson Reservoir, Prewitt Reservoir and North Sterling Reservoir.
4.
5. To determine the applicability of conventional TSI models using collected water quality, chlorophyll-*a* and transparency data.

METHODOLOGY

Nutrient concentrations, chlorophyll concentrations and physical parameters were measured at each reservoir on 10 sample days from April through October 2001. Seasonal nutrient changes and primary production were compared within and between the reservoirs. TSI and models for prediction of primary production were evaluated using 2001 nutrient and chlorophyll data.

Site Description

The South Platte Basin begins at an elevation of more than 4,267 meters along the continental divide. The basin has wide temperature and precipitation variation with the greatest precipitation in the mountains (> 76 centimeters annually) (USGS 1998). The average annual precipitation near the reservoirs, based on 30 years of data between 1960 and 2001, is 39.6 centimeters (minimum, 22.4; maximum, 52.3) (NOAA 2001). The South Platte characteristically exhibits a snowmelt hydrograph, however there is substantial flow alteration. Annual alterations in the natural hydrologic system include water diversion of more than 370,000 ha-m, water reservoir storage of more than 246,700 ha-m and importation of more than 49,300 ha-m from the Colorado Western Slope (USGS 1998). Primary land use changes from alpine near the headwaters, to urban along the front range, to a mixture of rangeland and agriculture downstream of Denver, Colorado (USGS 1998).

Three reservoirs in the South Platte River basin were selected for analysis: North Sterling Reservoir, Prewitt Reservoir and Jackson Reservoir. These reservoirs are located on the northeastern plains of Colorado, east of Fort Collins, Colorado (Figure 5). The reservoirs provide irrigation water rights to agricultural operations and recreational opportunities including boating, fishing and swimming.

Reservoir characteristics

All three reservoirs are filled with water from the South Platte River. The Jackson Reservoir inlet is near Master's Gage approximately 145 kilometers (90 miles) downstream of Denver. The inlet for both Prewitt and Sterling Reservoirs is approximately 81 kilometers (50 miles) downstream of the Jackson Reservoir inlet, or 225 kilometers (140 miles) from Denver, near the Balzac gage. The volume, depth and surface area change seasonally as the reservoir water is used for irrigation or replaced by reservoir filling (Table 4).

North Sterling Reservoir is the largest and the deepest of the reservoirs (Figure 6). The storage capacity of approximately 9,251 hectare-meters (ha-m) (75, 000 acre-feet) in early spring decreases through out the irrigation season. In 2001, the volume decreased from 9,254 ha-m (75,000 acre-feet) in May to 1,173 ha-m (9,500 acre-feet) in October (Yahn 2001). Most winters North Sterling Reservoir freezes over completely, but only for several weeks (Loomis 2001).

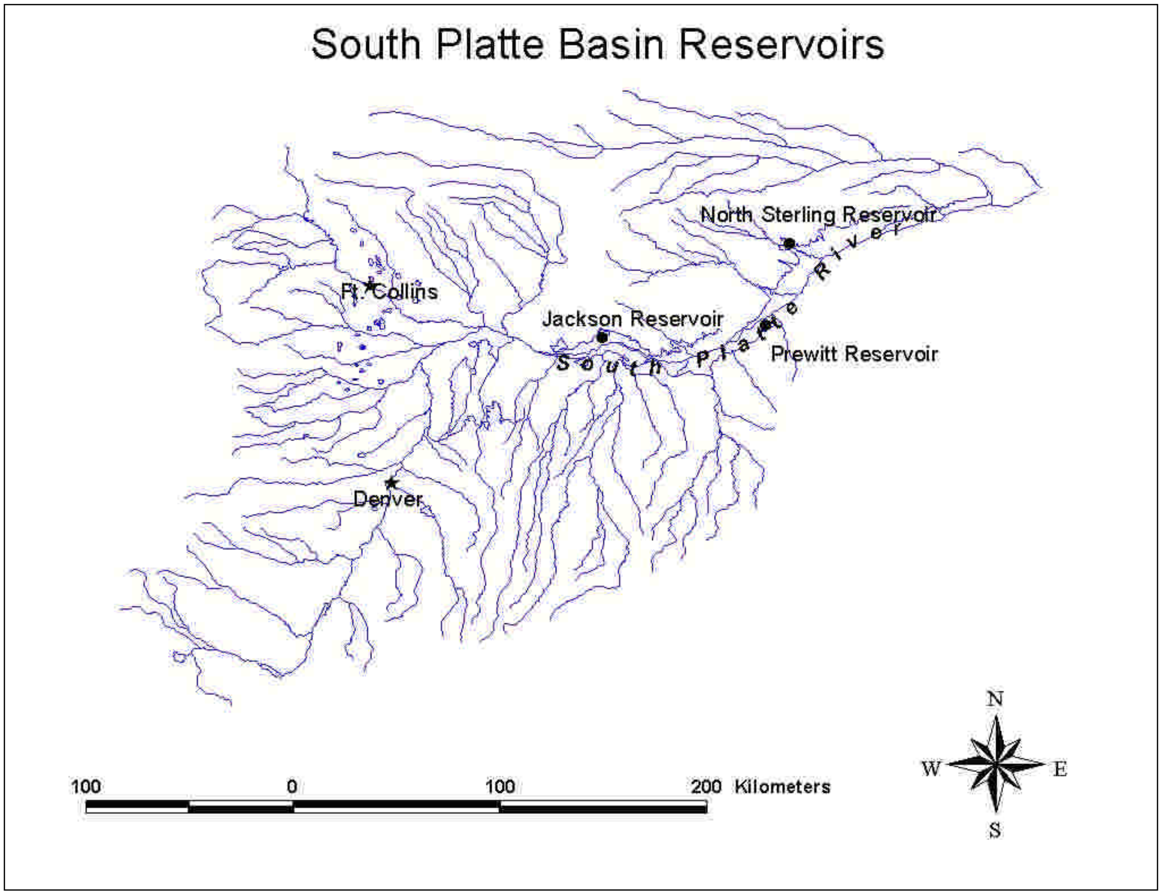

Figure 5: South Platte Basin Reservoirs Examined in the 2001 Study.

Table 4: Reservoir Physical Characteristics (Adapted from (Cooper 2001).

	Jackson	Prewitt	North Sterling
Capacity in acre-feet (ha-m)	35,629 (4,359)	28,840 (3,524)	74,010 (9,055)
Inlet canal length (km)	18	10	113
Surface Area in acres * (hectares)	2,600 1,052	900 364	2,880 1,165
Owner	Jackson Reservoir Co.	Logan Irrigation District	North Sterling Irrigation District
Manager	Colorado State Parks	Colorado Division of Wildlife	Colorado State Parks

* Colorado State Parks web page: http://parks.state.co.us/boating/lakereservoirs.html
Accessed February 19, 2001.

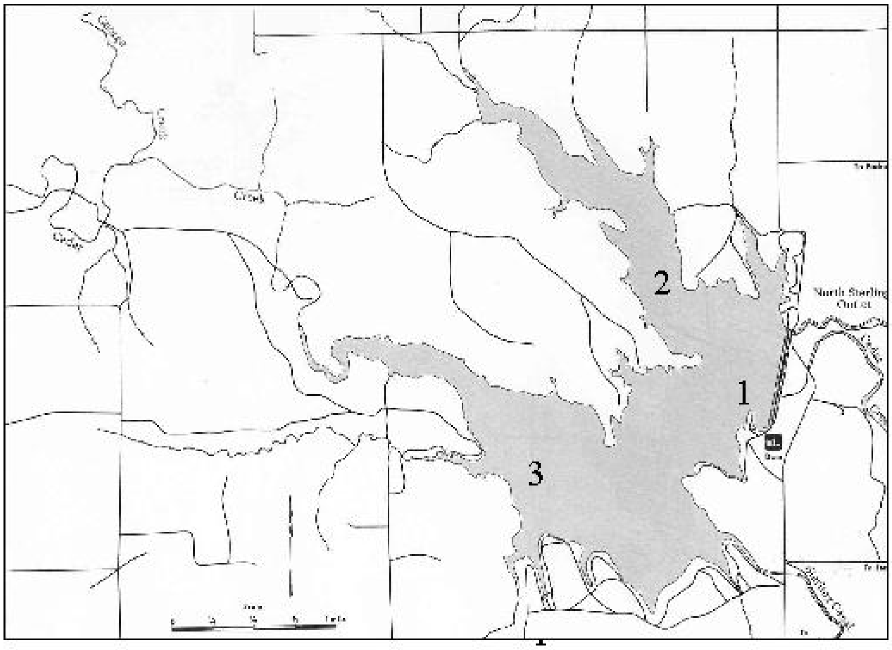

Figure 6: North Sterling Reservoir sample sites for the 1995 and 2001 reservoir studies (Adapted from Aquamaps, 1985).

Prewitt Reservoir was built with a capacity of 3,967 ha-m (32,160 acre-feet), but is restricted to a level of 3,528 ha-m (28,600 acre feet) by the Colorado State Engineer to ensure dam safety (Yahn, personal communication, 2001). Prewitt Reservoir supplies supplemental water rights, which causes varied outflows each year to provide for irrigation water rights. Some years water right holders will require their supplemental rights while in other years the water will remain in the reservoir throughout the season (Yahn, personal communication 2001). In 2001, the reservoir volume was 3,528 ha-m (28,600 acre-feet) in May and decreased to 1,495 ha-m (12,120 acre-feet) by November.

Jackson Reservoir was built in the early twentieth century and incorporated an existing lake (Aquamaps 1984) (Figure 7). Renovations on the dam at Jackson Reservoir began on August 10, 2001 and continued through December. Consequently the reservoir was closed to boating and the water level was low, but not uncharacteristically so since the reservoir volume in October 2000 (469 ha-m or 3,800 acre-feet) was less than the initial volume in during construction (625 ha-m or 5,064 acre-feet) (Vassios 2001).

Although the reservoirs differ in size, their management is similar. Boating is restricted or prohibited from October or November through the last day of migratory waterfowl season. The reservoirs are filled with South Platte River water during the winter, spring and into early summer. During the summer for at least several months, filling ceases and much of the reservoir volume is released to meet irrigation demands. Thus, reservoir inflow and outflow occurs at different times of the year. By the end of the irrigation season the reservoir volume has decreased by as much as 90% (Appendix A).

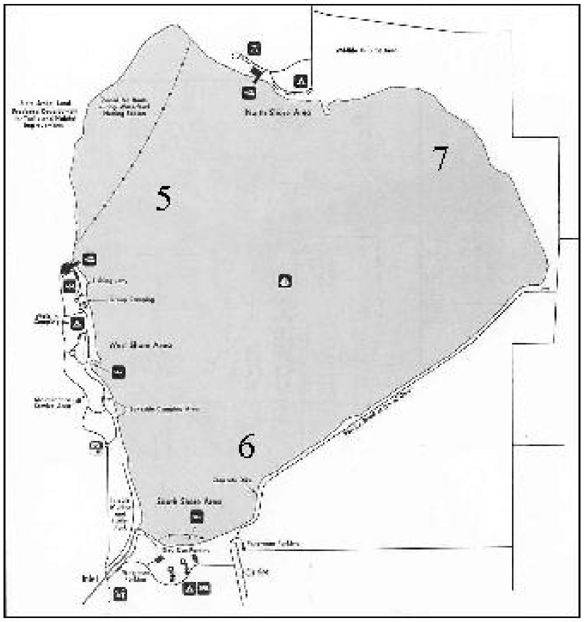

Figure 7: Jackson Reservoir sampling locations for the 1995 and 2001 studies (Adapted from Aquamaps, 1985).

Sampling location

Colorado State Parks provided boats to facilitate sampling at North Sterling and Jackson Reservoirs. Physical parameters, including Secchi disk depth, were collected at three sampling locations at both reservoirs, approximating the National Water Quality Assessment (NAWQA) sampling locations from the 1995 synoptic study. Physical parameters were collected at NAWQA sites 1, 2 and 3 on North Sterling Reservoir, which correspond with the same numbers in this study (Figure 6). All samples of Prewitt Reservoir were taken from the dock (Site 4) since boat access was not available. Physical parameters were collected at NAWQA sites 1, 2 and 3 at Jackson Reservoir, which correspond with sites 5, 6, and 7 in this study, respectively (Figure 7). The sample locations are approximate depending upon reservoir water level and boat drift due to wind.

Water Quality Measurements

This section describes the methods employed to gather water quality information. Sample collection and analysis methods for nutrients, chlorophyll-*a*, phytoplankton and physical parameters are described. Field and laboratory quality assurance and quality control measures are also reported.

Physical parameters

Physical data were collected using the Yellow Springs Instruments ® 6920 probe each sampling day except October 8, 2001. On October 8, 2001, Yellow Springs Instruments ® 600-XLM was used. The probe was calibrated for pH and specific conductance in the laboratory prior to sampling and verified in standard solutions upon returning to laboratory following sample collection. The dissolved oxygen membrane was visually examined and batteries checked in the lab prior to sampling. The probe was calibrated for atmospheric pressure and dissolved oxygen in the field prior to the first data collection each sampling day. Date, time, temperature (°C), specific conductance (μs/cm), dissolved oxygen (mg/L and percent), and oxygen reduction potential (mV) were collected at each sampling site and at depth.

Nutrient sample collection and analysis

Ten water quality samples were taken for nutrient analysis at each reservoir (North Sterling, Jackson and Prewitt) between April and October 2001. Samples were collected between two and four weeks apart, with more frequent sampling in June, July and August. Sample collection occurred on various days of the week to minimize sampling bias. It was assumed that the reservoirs were well mixed with respect to nutrients. Samples were collected at approximately the 0.5 meter depth from the boat as grab samples in 1 liter HDPE bottles. This sampling depth is appropriate for use when identifying the limiting nutrient since water samples should be restricted to the epilimnion where most primary production occurs (Ryding and Rast 1989). Water samples for nutrient analysis were collected within 1 meter of the bottom of the reservoir on two days using a Van Dorn (APHA 1995) sampling bottle in both North Sterling

Reservoir (one sample) and Jackson Reservoir (two samples). No boat access at Prewitt Reservoir precluded depth sampling. All samples were stored at 4° C on ice packs after collection.

Nutrient samples were delivered directly to the Colorado State University Soil, Water and Plant Testing Laboratory (CSU) laboratory for analysis or stored in a refrigerator until delivery to the laboratory within 48 hours. Laboratory analysis for ammonia, nitrate, organic nitrogen, TP and PO_4^{3-} was completed using the methods with detection limits listed in Appendix B. Nitrite was analyzed on five days, but not considered part of the regular sampling scheme because it quickly converts to nitrate in natural waters. CSU detection limits for nitrogen and phosphorous species were 100 μg/L and 1 μg/L, respectively.

The automated phenate method was used for ammonia nitrogen analysis. Nitrite was determined using ion chromatography and samples were analyzed for nitrate using the cadmium reduction method. TKN, which determines ammonia and organic nitrogen, was analyzed using the semi-micro Kjeldahl method. TP and PO_4^{3-} analysis was completed using ICP and the Ascorbic acid method, respectively. Spectrophotometric determination was employed in chlorophyll-*a*, *b* and *c* analysis. Several of the analytical techniques differ between the two studies (Sprague, 2002), but should not affect sample comparability. Nutrient samples were transported on ice in both studies. (Kimborough, written communication, 2002).

Chlorophyll sample collection and analysis

Chlorophyll-*a* and nutrient samples were collected at the same sample site on the same sample date. The samples were collected in the field and filtered through glass fiber filters in the lab on the day of sample collection (excluding April 10, May 15 and June 8 samples). All filtered samples were dried using paper towels, filters were folded in half, frozen and sent on ice to the Bureau of Reclamation Laboratory in Denver for chlorophyll-*a,* chlorophyll-*b* and chlorophyll-*c* analysis. Chlorophyll analysis was completed using Method 10200 H2, the spectrophotometric determination of chlorophyll (APHA 1995). Phaeopigment analysis was completed on samples taken in April, May, and early June using the spectrophotometric method (APHA, 1995).

Phytoplankton Identification

At least one grab sample was taken from each reservoir on each sampling date for alga identification. In shallow areas of 2-3 meter depth, a subsurface grab sample for plankton between 0.5 and 1 meter may be adequate (APHA 1995). Samples were stored in an ice chest and refrigerator until analysis was completed within seven days. A wet mount slide was prepared and live samples were analyzed. A Leitz-Wetzlar SM-LUX microscope was used in identifying algae present. The goal of this analysis was to compile a general list as a record of some alga genera present at the sample sites over the season.

Quality assurance and quality control

Field duplicates were collected as quality assurance samples and analyzed for chlorophyll-*a* or nutrients. Approximately 25% of the samples collected had duplicate samples collected for quality assurance purposes (14 of 59 samples). The duplicate samples were collected one after another at approximately the same point in the reservoir and analyzed as two discrete samples (Stednick and Gilbert 1998). Laboratory duplicates for chlorophyll-*a* analysis were completed on approximately 10% (Stednick and Gilbert 1998) of the chlorophyll-*a* samples (3 of 29 samples). The same volume of one sample was filtered through two different glass fiber filters and analyzed using the same procedures to compare results. The nutrient samples were subject to the CSU lab internal quality control program (Self 2002).

Data management and analysis

A Microsoft Excel ® spreadsheet was used to manage the data for this research. Physical data were recorded in the field by the YSI ® Kermit 610, downloaded as an Ecowinn ® data file and converted to a comma delimited text file for each sample site. The comma delimited text files were then imported into Microsoft Excel ® and saved as separate files under a specific naming pattern (date_reservoir_site). All physical data for each date was stored in separate files on floppy and 100 MB zip disks. The nutrient, chlorophyll-*a* and physical data were merged into a common database and organized by date and site.

Statistical Methods

Microsoft Excel ® and SAS Version 8.0 (SAS, 1999) were used in the Windows platform to complete statistical analysis. For all statistical analysis, values below the detection limit were treated as zero.

Several methods were used to evaluate physical parameters and reservoir mixing. A graphical depiction of water temperature, pH and dissolved oxygen change with depth was used. Since the reservoir water levels fluctuate greatly over the season, the graphs depict reservoir water elevation in relation to the seasonal maximum water elevation.

Thermal stratification was evaluated for North Sterling and Jackson Reservoirs. A change of 1° C or more per meter of depth is defined as a thermocline (Wetzel 2001). When possible, thermal change was evaluated at each meter depth. If the depth between measurements was greater than one meter, but the temperature change was less than 1° C then the assumption that temperature between any two points equaling one meter was less than 1° C was made. Water temperature between 0 - 1, 1 - 2 and 2 - 3 meters was compared for each sample site on each sampling date. If multiple measurements were available for each interval, their values were averaged. Days with a change of 1° C or less from the water surface to the deepest measurement were summarized in tabular form for Jackson and North Sterling Reservoir.

Along with graphical evaluation, the dissolved oxygen and pH profile was evaluated by subtracting the value at the deepest point from the greatest value at the surface (0 - 1.5 meters). The difference was compared between sites and days.

The general statistics of sample size, minimum, mean, median and maximum were reported for nutrient and chlorophyll concentrations at each reservoir. Nutrient ratios are evaluated, along with nutrient concentrations, on each sampling date to determine the limiting nutrient. Nutrient trends are evaluated graphically. A comparison of the nitrate trend for the two years is accomplished graphically by plotting the nitrate values for both years on the same graph as discrete data points.

Correlation and regression between the total and bioavailable nutrients and chlorophyll-*a* was completed in SAS. All values were converted to μg/L (mg/m^3) prior to taking the logarithm. A constant (1) was added to the entire data set. The logarithm was computed to normalize the data prior to regression and correlation. The correlation coefficient (r) and the p-value for testing the null hypothesis that the true correlation is zero are reported.

TSI and Model Spreadsheet Development

A Microsoft Excel ® workbook was developed to evaluate trophic relations for this study and designed for future use by reservoir managers. The workbook consists of two spreadsheets, the first of which contains 24 common nutrient-chlorophyll models. The second spreadsheet uses three common TSI to determine the trophic state based upon input values. The spreadsheet allows user input of measured values (TP, chlorophyll-*a*, Secchi disk depth and TN), which are used in the equations and TSI.

In order to compare the effectiveness of common nutrient~chlorophyll-*a* models, the first spreadsheet was developed to compute five measures of precision between the computed and observed chlorophyll-*a* values (Canfield 1983, Brown 2000):

1. Pearson's correlation coefficients between measured and calculated chlorophyll –a.

2. Pearson's correlation coefficients between the logarithm of the measured and calculated chlorophyll-*a* values.

3. 95% confidence limits for calculated chlorophyll-*a* concentrations from the standard deviation of the mean difference of the logarithms of measured and calculated values. The user must input the appropriate z value based upon the number of samples. The confidence limits are computed as the standard deviation * z +/- the mean.

4. Average error is computed using untransformed values as the mean of the absolute value of the difference between measured and calculated values.

5. Percentage error is the mean of the same differences standardized by dividing by the measured value and multiplied by 100 to express the value as a percent.

The second spreadsheet compared reservoir classification determined by different TSI to evaluate their applicability to Eastern Colorado reservoirs in the South Platte Basin. The worksheet allows the input of data and computes the resulting index and classification (oligotrophic, mesotrophic or eutrophic) based upon each parameter. The final results can then be compared.

RESULTS

This chapter reports the physical parameter, water quality and trophic status results for the study. Changes in reservoir volume and depth are also reported.

Reservoir volume, depth and sampling locations

Reservoir volume decreased over the study period at all three reservoirs (Figure 8); (Appendix A). Reservoir volume at North Sterling Reservoir decreased from over 9,000 ha-m to less than 1,000 ha-m over the study period (Figure 8). For approximately three months no filling occurred at North Sterling Reservoir. Filling occurred from January through mid-June and resumed in late September. Outflows from North Sterling Reservoir began in April and continued through September 21, with an additional flow for approximately one week in October.

The maximum capacity of Prewitt Reservoir is approximately one-third that of North Sterling Reservoir. The initial volume of 3,500 ha-m was drawn down to less than 1,500 ha-m. By the end of the season the reservoir volume at Prewitt Reservoir was slightly more than half of the initial volume (56%). Prewitt Reservoir was filled from January through mid-June with additional filling on three days in July. Excluding several days in April, reservoir outflows occurred from mid-June through mid-September.

Jackson Reservoir, like Prewitt Reservoir, had a maximum volume of roughly 3,500 ha-m. In 2001, Jackson Reservoir volume decreased from over 3,000 ha-m to approximately 630 ha-m by early August to accommodate dam construction. In 2000, Jackson began with over 3,000 ha-m and decreased to roughly 680 ha-m by early August. Thus, even though construction was occurring, the reservoir volume decreased to similar levels by August in both years.

Variations in maximum depth at each sample site were due to declines in reservoir volume and sample site approximation (Appendix B). The sample site with the deepest reservoir depth (site 1) was near the dam at North Sterling Reservoir. The depth ranged from 13 to 3.3 meters. The maximum depth at site 2, in the North (Darby) arm of Sterling Reservoir, ranged from 11.5 to 1.6 meters. The maximum depth at Site 3, near Goose Island in the Southern (Cunningham) arm of North Sterling Reservoir, ranged from 8.5 to 0.9 meters. Reservoir access at Jackson Reservoir was only available on 6 of the 10 sampling days. Site 5 at Jackson Reservoir is near the Southern boat ramp and ranged in depth from 5.5 to 1.4 meters. Site 6, near the Jackson Reservoir dam, had a depth ranging from 3.8 to 2.1 meters. Site 7 had a depth ranging from 3.6 to 1.3 meters. In general, the maximum depths declined less at Jackson Reservoir (1.7 to 2.8 meters) than North Sterling Reservoir (7.6 to 9.9 meters) due to differences in bathymetry and volume.

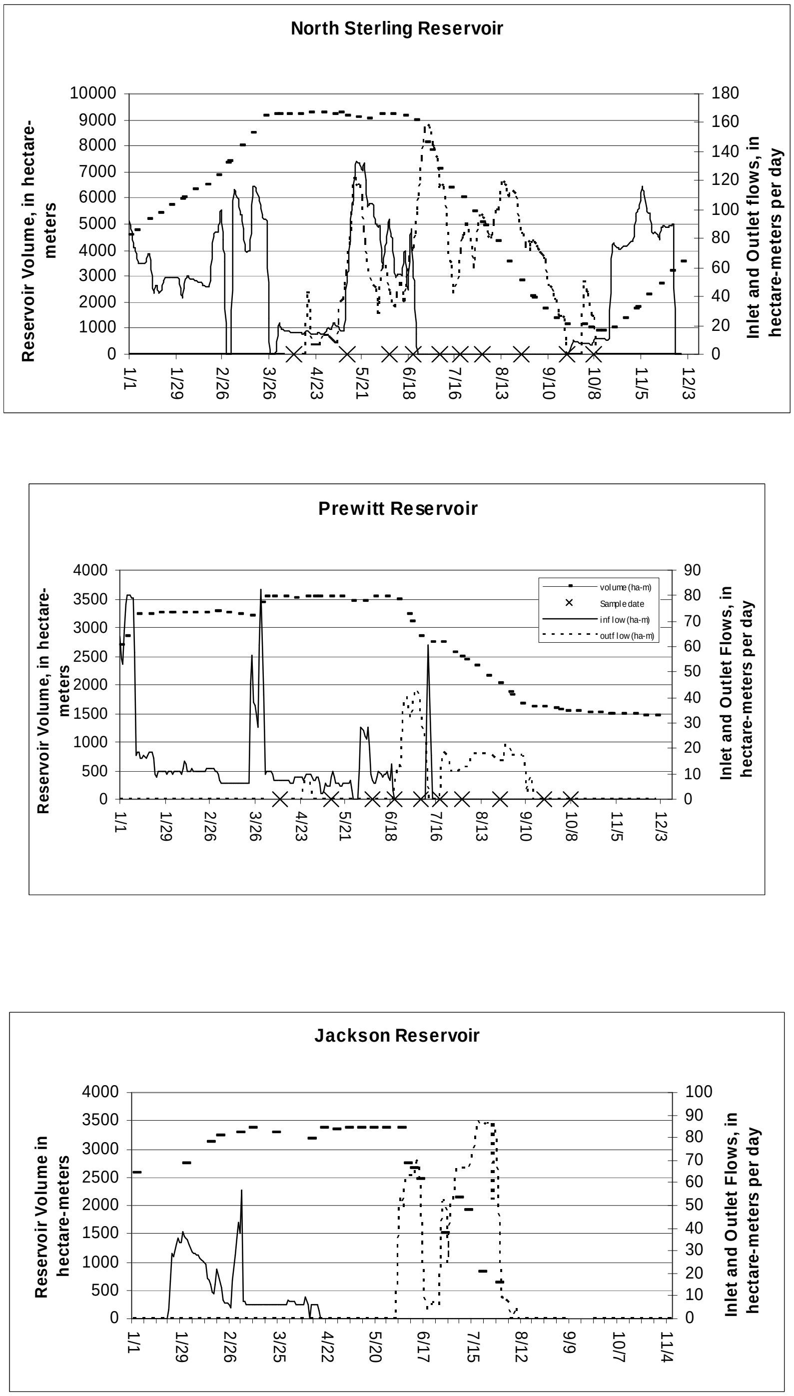

Figure 8: North Sterling, Prewitt and Jackson Reservoir change in volume, inflow and outflow over time from January through November 2001. (Source: North Sterling Irrigation District, Jackson Reservoir Irrigation Co., and CO Div. Of Water Res.).

Changes in reservoir volume and reservoir access influenced sampling locations. Samples were taken from the dock on the first sampling day at all three reservoirs, all sampling days at Prewitt Reservoir and on the last three sampling days at Jackson Reservoir. Therefore, depth profile data collection was not possible on several days. All other samples were collected from a boat at sample sites that corresponded with those used in the 1995 NAWQA study. Approximate sampling coordinates for the sites were recorded using a GPS 12-personal navigator (Garmin) on July 19, 2001 (Appendix B). Nutrient samples were typically collected at the same sample sites on each sample date, excluding the first sampling day and the last three at Jackson Reservoir (Appendix B). Nutrient samples at North Sterling Reservoir were collected at sample site 1, typically the deepest sample site, excluding May 12 when nutrient samples were collected at site 2. Nutrient samples at Jackson Reservoir were collected at Site 5, also typically the deepest sample site, excluding the first and last three sampling days. Three nutrient samples were collected at the surface and a depth of between 5 and 8 meters to compare values.

Physical Characterization

This section describes reservoir mixing and seasonal changes in the depth profiles of temperature, dissolved oxygen and pH at North Sterling and Jackson Reservoir and surface water physical parameters at Prewitt Reservoir. Seasonal changes in Secchi disk depth are also reported. Physical data for North Sterling, Prewitt and Jackson Reservoirs are located in appendices C.1. Secchi disk depth is in Appendix C.2.

Temperature

Reservoir water temperature at North Sterling Reservoir ranged between 10° C and 25° C over the study period, but the reservoir was thermally well mixed on each sampling day. North Sterling Reservoir showed little thermal variation from surface to the maximum depth (Figure 9). A temperature change of 1°C or less from the surface to depth at North Sterling Reservoir was observed on 15 of 27 profiles, or 56% of the time (Table 5). Depth profiles from seven sampling dates on North Sterling Reservoir were used to evaluate temperature changes with each meter increase in depth. Site 3 on July 5 had a change of 1.1° C in a measured depth of 1.5 meters. Since the depth interval is greater than 1 meter, and no data are available for a smaller interval, it is possible that this temperature change occurred within a one-meter interval. On July 17, temperature in the deep waters of site 1 changed more than 1° C per meter between 10.6 - 11.6 meters (1.2° C) and 11.6 - 12.6 meters (1° C). Thus, only at one sampling site on one sampling day was there evidence of the existence of a thermocline, defined as a temperature change of more than 1° C per meter (Wetzel 2001).

Jackson Reservoir typically showed a temperature change of 1°C or more from the reservoir surface to maximum depth (Figure 10). A temperature change of 1°C or less from the reservoir surface to depth was only observed on 3 of 18 profiles at Jackson Reservoir, or 17% of the depth profiles (Table 5). Jackson Reservoir showed at least one temperature change of more than 1° C per meter at each site on five of six sampling dates. The exception was July 5, 2001 when no temperature change of greater than 1° C from the reservoir surface to maximum depth at any of the sites was observed.

Over the season the surface water temperature at North Sterling Reservoir in the 0 - 1 meter interval ranged from approximately 14° C in May and October to a maximum of 26° C in July. Typically, the range in surface temperature at the three sampling sites varied by less than 2° C. Surface water temperature at Prewitt Reservoir ranged from 11°C in April to 27 ° C in July. Surface water temperature was similar at Jackson Reservoir with a range of 10° C to 28 °C.

Mean water temperature of all sample sites at Jackson and Sterling Reservoirs between 0-3 meters was computed. Water temperature was between 0.4 - 2.85 °C higher at Jackson Reservoir than North Sterling Reservoir. At North Sterling and Jackson Reservoir, differences in mean water temperature in the 0-3 meter depth between sample sites ranged from 0.3-2.4 ° C.

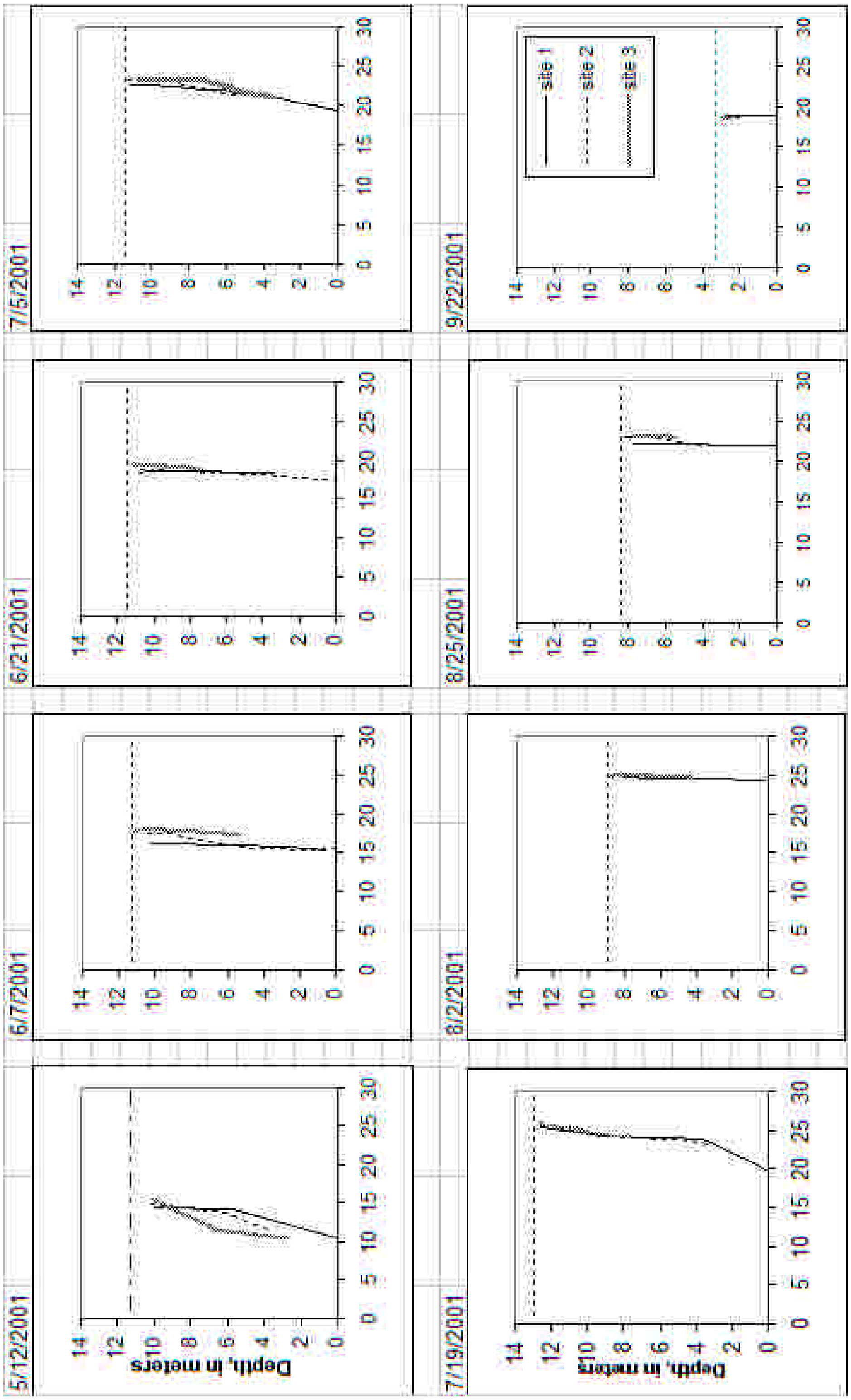

Figure 9: Change in water temperature (°C) based on depth at North Sterling Reservoir between May and September 2001.

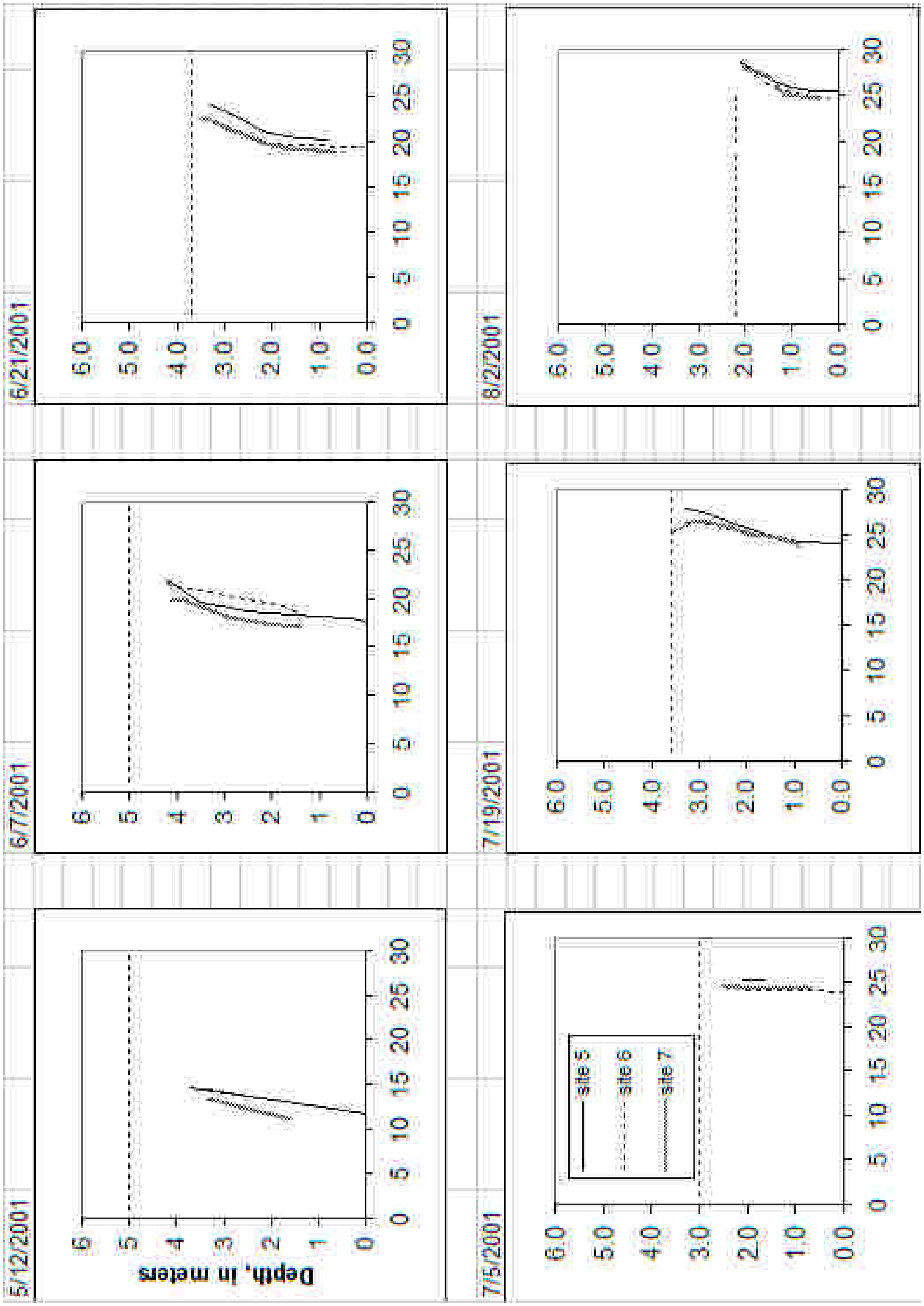

Figure 10: Change in water temperature (°C) based on depth at Jackson Reservoir between May and August 2001.

Table 5: Surface to depth water temperature change of 1° C or less at North Sterling and Jackson Reservoirs from May - October, 2001.

	North Sterling Reservoir			Jackson Reservoir		
Date	Site 1	Site 2	Site 3	Site 5	Site 6	Site 7
4/10/01	--	--	--	--	--	--
5/12/01						
6/7/01	X		X			
6/21/01	X	X				
7/5/01				X	X	X
7/19/01						
8/2/01	X	X	X			
8/25/01	X		X	--	--	--
9/22/01	X	X	X	--	--	--
10/8/01	X	X	X	--	--	--

-- indicates that depth profile information was not available

Dissolved Oxygen

In general, dissolved oxygen (DO) concentrations decreased as water depth increased at North Sterling and Jackson Reservoirs. The greatest difference in dissolved oxygen concentrations from surface to depth occurred on July 19 in both North Sterling Reservoir (12 mg/L) and Jackson Reservoir (12 mg/L).

At North Sterling Reservoir the dissolved oxygen concentrations were typically lower during the summer for the entire profile and higher during the spring and fall (Figure 11). The mean of all measurements and sample sites for each sampling day from May to September shows May and September with the highest concentrations, 11.7 and 9.6 mg/L, respectively. The lowest overall dissolved oxygen concentrations were measured in July and early August with concentrations between 4.5 and 4.9 mg/L. Mean surface water dissolved oxygen concentrations within the first meter ranged from 7.2 mg/L in early June to the highest concentration of 11.4 in mid-July without showing any trend.

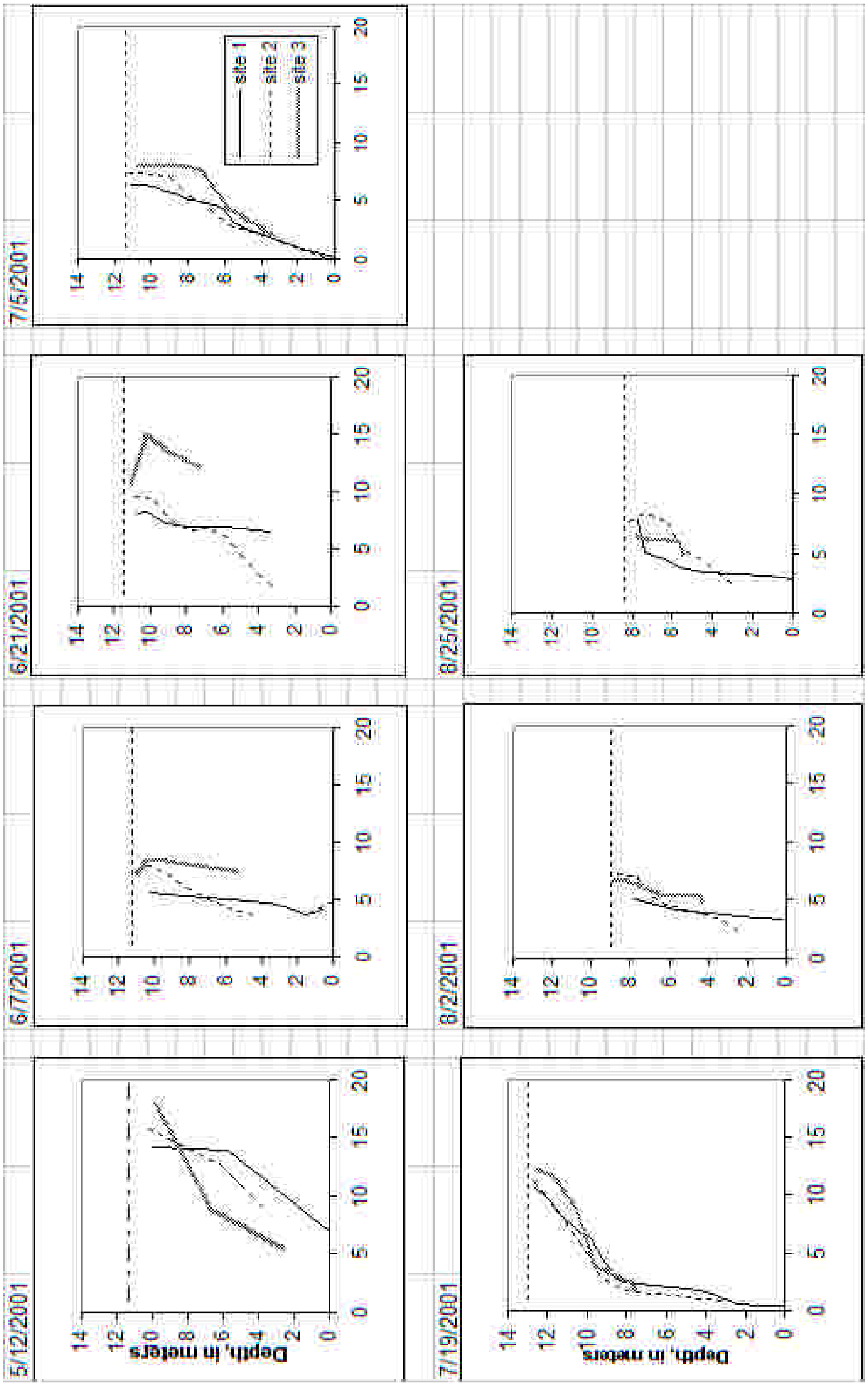

Figure 11: Change in dissolved oxygen concentrations (mg/L) based on depth at North Sterling Reservoir between May and August 2001.

The dissolved oxygen profile in North Sterling Reservoir shows a decrease in dissolved oxygen with depth (Figure 11). On three of the sampling days in July and early August, the dissolved oxygen at the bottom of the reservoir decreased to less than 1 mg/L (Appendix C.1).

The difference between the highest dissolved oxygen concentration at the surface (0 - 1.5 meters) and that of the deepest sample point at North Sterling and Jackson Reservoir was compared (Table 6). At North Sterling Reservoir, the decrease in dissolved oxygen from the surface to the bottom varied (> 2 mg/L) between the three sampling sites. For example, dissolved oxygen decreased at site 1 by 1.67 mg/L and at site 2 by 8.37 mg/L from the surface to depth on June 21, 2001. Similar variability was apparent on four other sampling days showing a large degree of variation in dissolved oxygen concentrations throughout the reservoir. In July, the difference in dissolved oxygen concentrations from the surface to depth at all samples sites was similar (< 2 mg/L). Twenty five percent of the profiles showed a decrease of less than 2 mg/L from the surface to depth.

Jackson surface dissolved oxygen measurements taken on 4 of 10 sampling days ranged from 8.3 to 10.2 mg/L. Depth profiles were measured on 6 of 10 sampling days at Jackson Reservoir. In general, dissolved oxygen concentrations decreased with depth (Figure 12). 15 of 18 profiles showed a dissolved oxygen decrease from surface to depth of greater than 2 mg/L (Table 6). The remaining profiles (3) showed a dissolved oxygen decline of less than 2 mg/L. Similar to North Sterling Reservoir there was a difference in the dissolved oxygen change from surface to depth among the three sample sites per sampling day.

Table 6: Decrease in dissolved oxygen concentrations (in mg/L) from the reservoir surface (0-1.5 meters) to the maximum depth

Reservoir	Site	Sampling Date						
		5/12	6/7	6/21	7/5	7/19	8/2	8/25
North Sterling Reservoir	1	7.22	1.40	1.67	6.22	10.17	1.82	5.25
	2	6.73	3.24	8.37	7.54	10.51	5.1	6.22
	3	12.57	.98	2.84	6.12	11.64	1.89	1.82
Prewitt Reservoir	4	--	--	--	--	--	--	--
Jackson Reservoir	5	-0.79	4.08	1.40	0.15	11.29	5.16	--
	6	3.8	4.82	2.3	2.88	2.94	5.8	--
	7	6.26	2.61	2.26	0.82	12.36	4.75	--

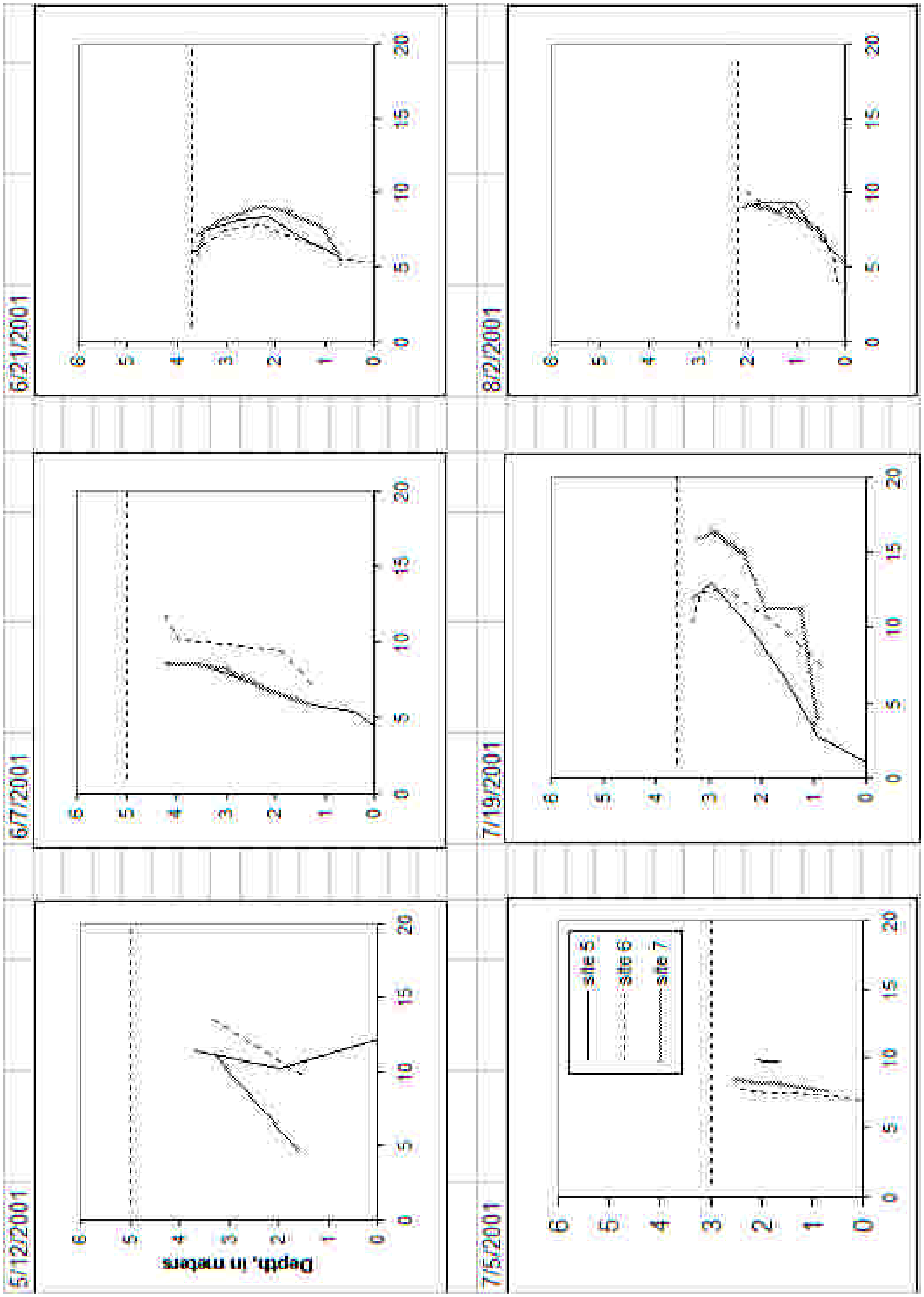

Figure 12: Change in dissolved oxygen concentrations (mg/L) based on depth at Jackson Reservoir between May and August 2001

Surface dissolved oxygen measurements at Prewitt Reservoir ranged from 8 to 14 mg/L over the season. The dissolved oxygen concentration was less than 10 mg/L for samples taken between June 20 and August 2, and greater than 10 mg/L for the remaining samples.

pH

On most sampling days pH decreased with depth at North Sterling and Jackson Reservoirs. Depth profiles of pH were collected on eight of ten sampling days at North Sterling Reservoir (Figure 13). Site three often had a slightly higher pH than sites 1 or 2; the mean value for pH from sites 1, 2, and 3 was 7.9, 8.0 and 8.2, respectively. The difference in pH from surface to depth was greatest in early and mid July (0.6 and 0.8, respectively), the days with the greatest change in temperature and dissolved oxygen in the reservoir. The pH change from surface to depth was not greater than 1 on any sampling day or site. The mean difference in surface pH at the three North Sterling Reservoir sites was 0.25. Overall, the average pH was 8.0 with a range of 7.2-8.9 from 229 measurements.

Depth profiles were collected at Jackson Reservoir on 6 of 10 sampling days showing pH decreases with increased depth (Figure 14). The difference in pH from surface to depth decreased for 17 of the 18 profiles measured. The difference from surface to depth was greatest on July 19 with a mean of the three sites of 0.86; a pH change of greater than 1 unit was observed at two of the three sampling sites on July 19.

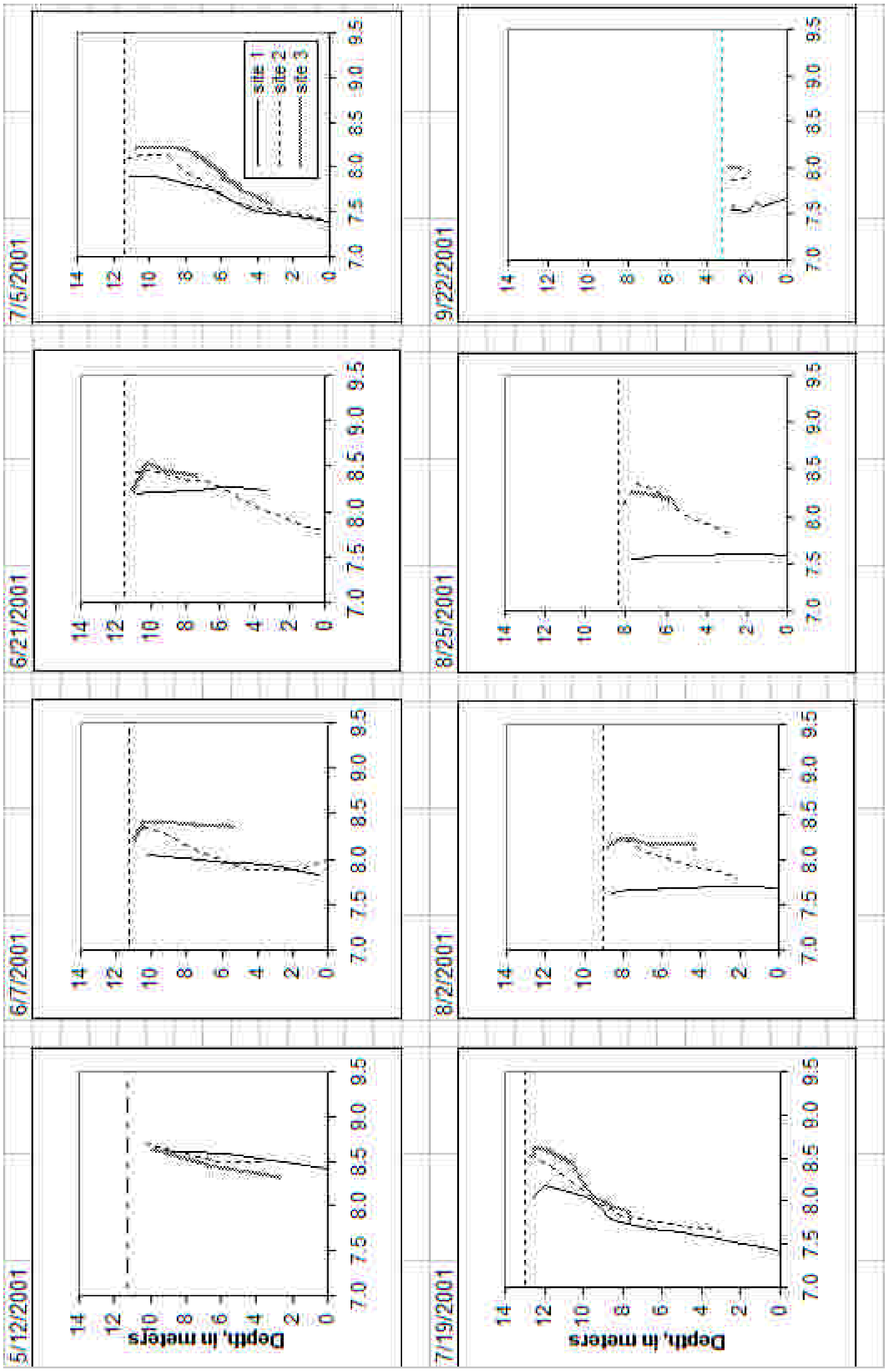

Figure 13: Change in pH based on depth at North Sterling Reservoir between May and September 2001.

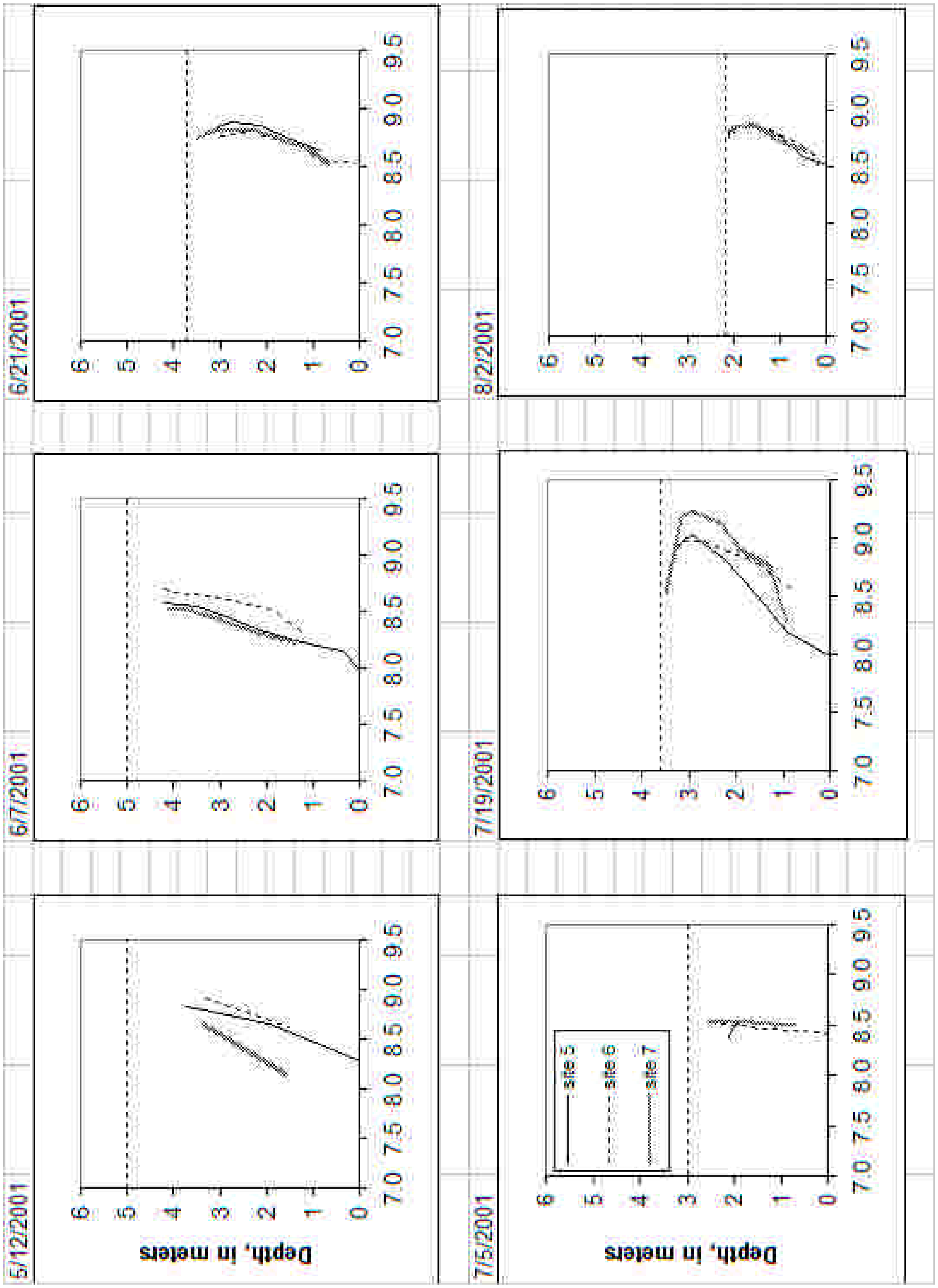

Figure 14: Change in pH based on depth at Jackson Reservoir between May and August 2001.

All other profiles had a pH change of less than 0.6 from surface to depth. The mean difference in surface pH between the three sites was 0.15. The mean pH at Jackson was 8.6 with a range of 7.7 - 9.2.

The mean pH at Prewitt Reservoir was 8.9 with a range of 8.3-9.3.

Secchi Depth

Secchi disk measurements were made at each reservoir on each sampling day excluding the last two sampling days at Jackson Reservoir (Appendix C.2). Secchi depth at Prewitt Reservoir was typically less than North Sterling and Jackson Reservoirs with overall means of 0.3, 0.6 and 0.5 meters, respectively. In general, the Secchi disk depth decreased from June and July through September (Figure 15). The Secchi depth range (n=26) at North Sterling Reservoir was 0.3 to 1.3 meters. The Secchi depth range from 10 measurements taken from the dock of Prewitt Reservoir was 0.15 to 0.4 meters. The Secchi disk depth range from 18 measurements at Jackson Reservoir was 0.2 to 0.9 meters.

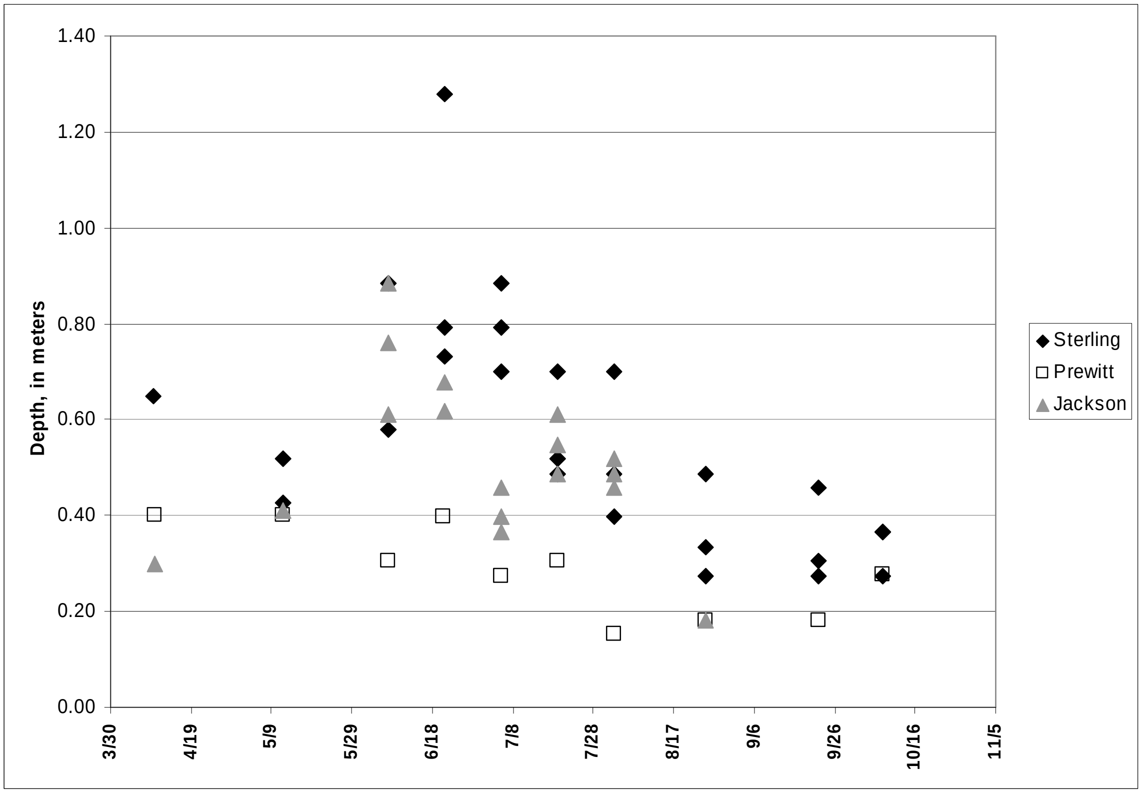

Figure 15. Secchi disk depth measurements at Jackson, Prewitt and North Sterling Reservoirs in 2001.

Reservoir Water Quality

This section reports reservoir nutrient concentrations and correlations between total and inorganic nutrients with primary production. Correlations are computed for eight sampling days at the three reservoirs from June 8 through October 8, 2001. Seasonal nutrient trends, ratios and mean nutrient values for April - October are also reported.

Reservoir nutrient and chlorophyll concentrations

Ammonia, nitrate, TKN and TP were sampled and analyzed on 10 days between April and October 2001 (Appendix C.3). Orthophosphate (PO_4^{3-}) was measured on each sampling date except the first. Nitrite was also measured, but not on each sampling date (Appendix B) since it quickly converts to nitrate in natural waters. Chlorophyll samples were collected and analyzed for the same 10 days (Appendix C.4), but measurements for the first two days are not included in the statistical analysis due to holding time concerns. No holding time is listed in standard methods for chlorophyll determination, but samples should be filtered for analysis relatively quickly. Chlorophyll samples for the first two sample dates were stored at 4°C until filtration on June 8, 2001. Chlorophyll-*a* can degrade to phaeophytin which interferes with the spectrophotometric determination of chlorophyll because it absorbs light at the same wavelength (Wetzel and Likens 2000). Chlorophyll-*a* and phaeophytin values were determined for the first three sampling days, and pre and post acidification ratios are used to determine the physiological condition of the samples. A ratio of 1.7 indicates no phaeophytin is present and the sample is in good condition. A ratio of 1.0 indicates the entire sample is phaeophytin (APHA 1995). The average ratio for April and May samples was 1.21 and 1.50, respectively. The average ratio for the sample filtered the same day was 1.56. The proportion of the sample that was phaeophytin was between 65-75% in April, 23-35% in May and 7-38% in early June. Neither sample that was held without filtration was used in the statistical analysis. All chlorophyll-*a* and phaeophytin measurements are listed in Appendix C.4.

Nutrient and chlorophyll concentrations measured in Jackson, Prewitt and North Sterling Reservoirs in 2001 exceed EPA recommended numeric values for reservoirs in Ecoregion V (Table 3). The median TP measurements at Jackson, Prewitt and North Sterling Reservoirs were 208, 267 and 138 μg/L, respectively. Maximum TP concentrations of 650, 355 and 410 μg/L occurred at Jackson, Prewitt and North Sterling Reservoirs, respectively. These values exceed the typical lake TP concentration of 10 - 40 μg/L(Snoeyink and Jenkins 1980).

TN is the summation of TKN, nitrate and nitrite. The median TN concentrations were 2,550, 3,100 and 3,550 μg/L at Jackson, Prewitt and Sterling, respectively (Table 7).

Table 7: Nutrient and Chlorophyll concentrations for Jackson, Prewitt and North Sterling Reservoirs between April - October 2001.

		n	**min**	**median**	**mean**	**max**
Chlorophyll-*a* (μg/L)	Jackson	8	7	45	98	285
	Prewitt	8	81	142	156	307
	Sterling	8	27	46	61	130
Chlorophyll-*b* (μg/L**)**	Jackson	8	-0.2	3.35	7.30	25.1
	Prewitt	8	-2.7	0.10	0.18	9.7
	Sterling	8	1.4	3.615	4.7	11.8
Chlorophyll-*c* (μg/L**)**	Jackson	8	0.52	3.4	8.8	25.1
	Prewitt	8	2.4	8.62	9.11	22.5
	Sterling	8	1.6	2.86	4.15	8.1
NH_4-N (μg/L)	Jackson	10	0	400	450	1,200
	Prewitt	10	0	200	322	1,100
	Sterling	10	0	300	326	960
Nitrate (**μg/L)**	Jackson	10	0	500	760	2,700
	Prewitt	10	0	100	270	1,400
	Sterling	10	0	1,650	2,040	5,300
Nitrite (**μg/L)**	Jackson	5	0	100	60	100
	Prewitt	5	0	0	40	100
	Sterling	5	0	100	80	100
TKN (μg/L)	Jackson	10	800	1,950	2,780	6,200
	Prewitt	10	1,600	3,000	2,910	5,500
	Sterling	10	500	1,800	1,830	4,100
PO_4^{3-} (μg/L)	Jackson	9	0	24	52	137
	Prewitt	9	0	16	45	146
	Sterling	9	0	9	16	75
TP (μg/L)	Jackson	10	91	208	262	650
	Prewitt	10	173	267	260	355
	Sterling	10	53	183	190	410

The median chlorophyll-*a* concentrations at Jackson and North Sterling were similar, 45 and 46 μg/L, respectively. The median value at Prewitt Reservoir was approximately 3 times larger, 142 μg/L (Table 7). The median chlorophyll-*b* and chlorophyll-*c* concentrations were between 2.9 and 3.6 μg/L at Jackson and Sterling Reservoirs. Prewitt had a lower median chlorophyll-*b* (0.10 μg/L) and a higher median chlorophyll-*c* (8.62 μg/L).

The minimum value for the bioavailable nutrients (ammonia, nitrate, nitrite and PO_4^{3-}) was below detection limits for each reservoir. Median ammonia, nitrate and nitrite were all lower at Prewitt Reservoir than the other two reservoirs, but TKN and TP were higher at Prewitt Reservoir. Median ammonia concentrations ranged from 200 to 400 μg/L. The median nitrate concentration was greatest at North Sterling Reservoir (1,650 μg/L) as compared with Prewitt (100 μg/L) and Jackson Reservoirs (500 μg/L). This reflects a higher maximum nitrate concentration observed at North Sterling Reservoir in April.

Nutrient Trends

A decrease in TN from April through early August was observed at all three reservoirs (Figure 16). The concentrations remained low in North Sterling, but increased at Jackson and Prewitt between August and October. The range of TN concentrations was 8,300 – 1,700 μg/L at Jackson, 6,900 – 1,600 μg/L at Prewitt and 9,400 – 2,300 μg/L at Sterling.

Nitrate concentrations in North Sterling and Jackson Reservoirs showed a seasonal decline. Between April 10 and October 8, nitrate concentrations in North Sterling Reservoir decreased from over 5,000 μg/L to less than the detection limit of 100 μg/L (Figure 16). Similarly, concentrations at Jackson Reservoir decreased from 2,700 μg/L to at or below the detection limit through late July, August and September with a slight increase on the last sampling date in October. Nitrate was below detection limits in Prewitt Reservoir on four of the sampling days, but seasonal decline was not observed (Figure 16). Ammonium ranged from below detection to 1,100 μg/L with no seasonal pattern.

Jackson TP concentrations taken from the boat ranged from 142 to 350 μg/L. Samples taken from shore during construction had TP concentrations ranging from 212 to 650 μg/L (Figure 17). Prewitt TP concentrations ranged from 173 to 355 μg/L. North Sterling TP concentrations ranged from 53 to 410 μg/L, and did not show a seasonal trend.

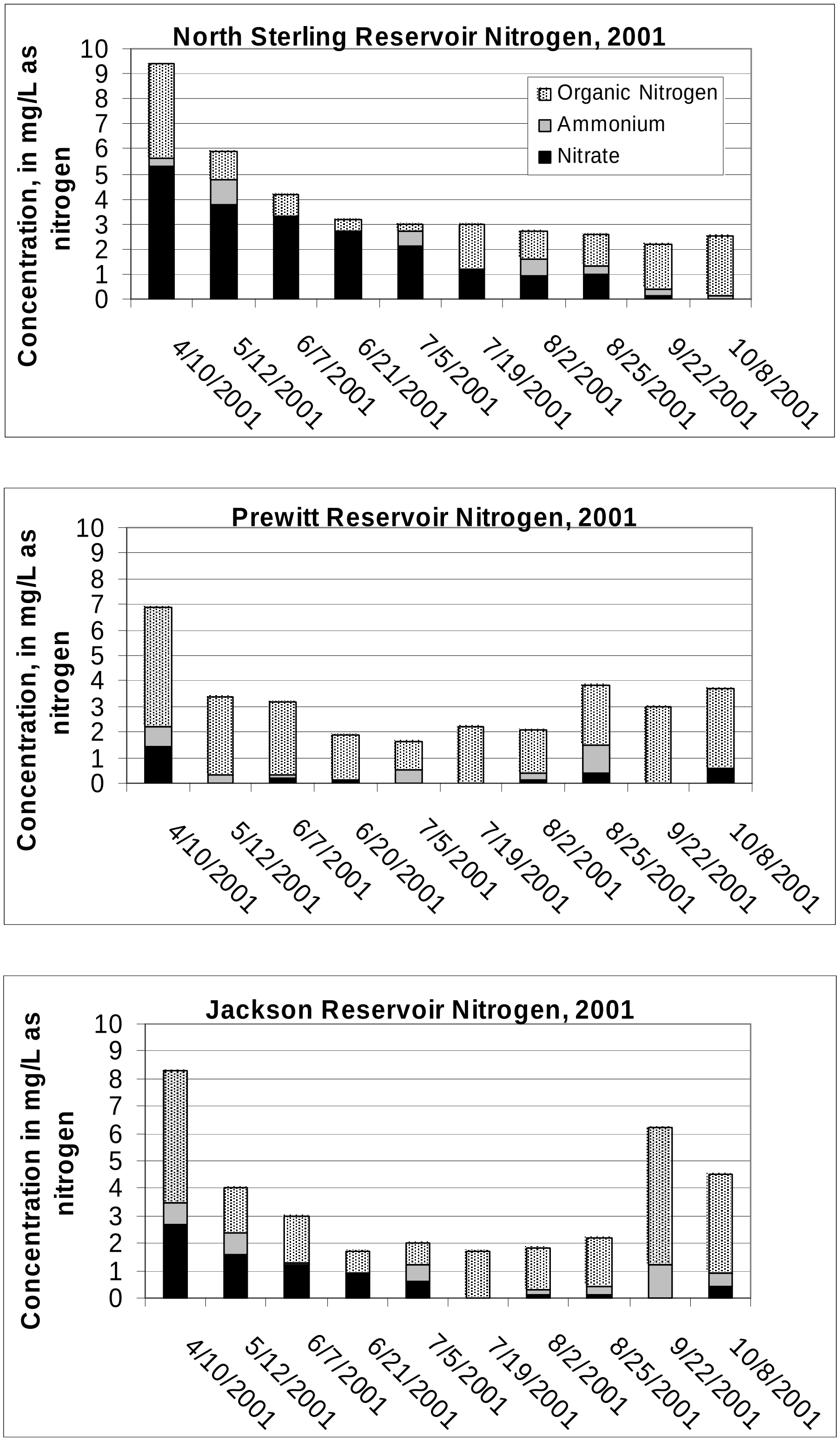

Figure 16. Nitrogen concentrations at Jackson, Prewitt and North Sterling Reservoirs between April and October 2001.

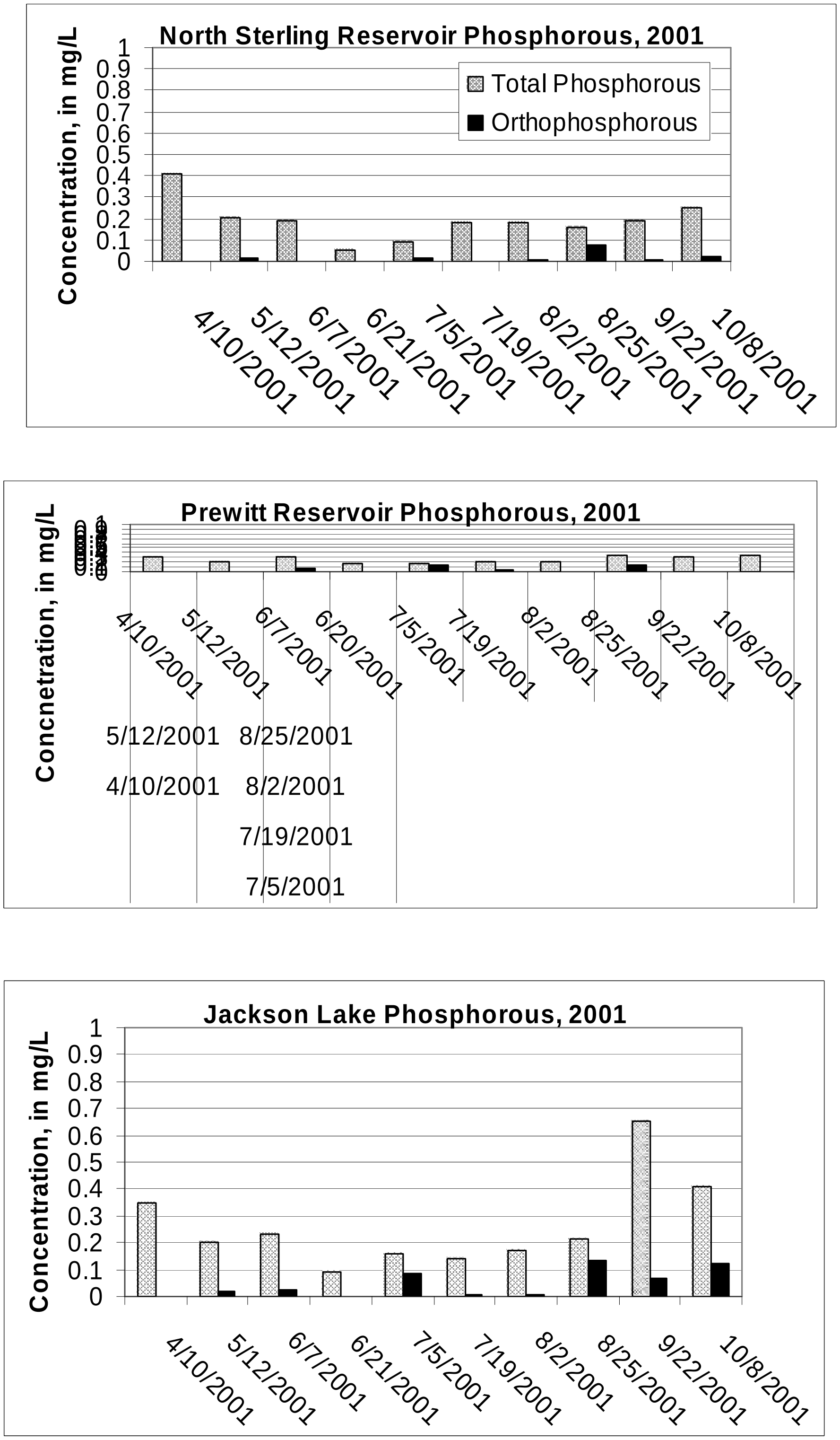

Figure 17: Phosphorous concentrations at Jackson, Prewitt and North Sterling Reservoirs between April and October 2001

Jackson Reservoir PO_4^{3-} concentrations ranged from 5 to 137 μg/L, excluding one sampling day with concentrations below the detection limit (Figure 17). Prewitt PO_4^{3-} concentrations ranged from 2 - 146 μg/L, excluding one sample below the detection limit. North Sterling PO_4^{3-} concentrations were below the detection limit of 1 μg/L in June, but ranged from 3 to 75 μg/L for the remainder of the sampling period. In general, TP concentrations decreased slightly in June and July, but increased again by the end of the study period. PO_4^{3-} showed no trend.

Chlorophyll-*a* concentrations increased over the summer, with chlorophyll-*a* concentrations for Prewitt being higher than those found in Jackson and North Sterling (Figure 18). The median concentration of chlorophyll-*a* at Prewitt Reservoir was 142 μg/L (Table 7). The median concentrations at Sterling and Jackson were 46 μg/L and 45 μg/L, respectively.

Samples were collected at North Sterling and Jackson Reservoir (surface and several depths) in the beginning of the study period to verify the assumption that the reservoirs were well mixed with respect to nutrients (Table 8). Samples were taken within 1 meter of the surface and within half a meter from the reservoir bottom. A third sample was also taken at North Sterling (6 meters) and Jackson (3 meters). The maximum difference in TP values taken at the surface and depth were 27 μg/L (North Sterling), 28 μg/L (Jackson; May) and 53 μg/L (Jackson; June). The PO_4^{3-} differences were 15 μg/L (North Sterling), 3 μg/L (Jackson; May) and 7 μg/L (Jackson; June). The differences in ammonia values taken at different depths were 420 μg/L (North Sterling), 220 μg/L (Jackson; May) and 100 μg/L (Jackson; June). Nitrate differences were 300 μg/L (North Sterling), 300 μg/L (Jackson; May) and 0 μg/L (Jackson; June). TKN differences were 400 μg/L (North Sterling), 500 μg/L (Jackson; May) and 800 μg/L (Jackson; June). All nutrient concentrations varied with depth, excluding nitrate concentrations in early June at Jackson Reservoir.

Nutrient Ratios

Nutrient ratios were used to evaluate the nutrient limiting primary production. In general, concentrations of biologically available phosphorous (PO_4^{3-}) less than 5 μg/L indicate potential PO_4^{3-} limitation and concentrations of biologically available nitrogen (inorganic-N) less than 20 μg/L indicate inorganic nitrogen limitation (Ryding and Rast 1989). Concentrations decreased to below these PO_4^{3-} levels at Sterling (3 days), Prewitt (2 days) and Jackson (1 day). Concentrations were below 100 μg/L and potentially below these levels of inorganic-N at Prewitt (1 day) and at Jackson (1 day); (Table 9).

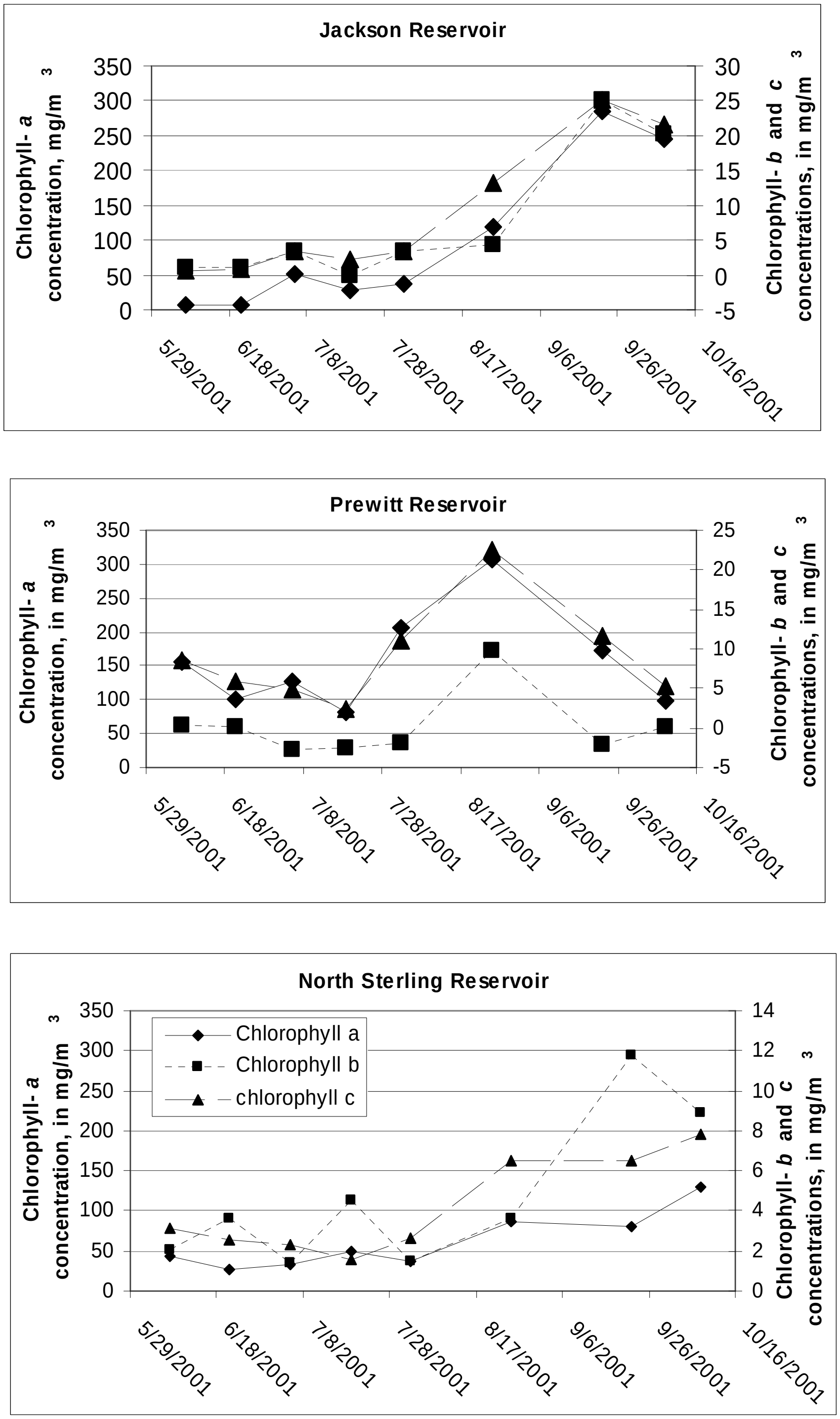

Figure 18: Chlorophyll concentrations at Jackson, Prewitt and North Sterling Reservoirs between June and October 2001.

Table 8: Nutrient concentrations (in µg/L) measured at the reservoir surface and bottom in May and June, 2001

	Date	Site	Depth	NH_4-N	NO_3-N	TKN	Total P	Ortho-P
North Sterling Reservoir	5/12/01	2	1 meter	960	3,800	2,100	201	15
		2	6 meters	540	4,000	1,700	228	15
		2	8 meters	900	3,700	1,800	223	<1
Jackson Reservoir	5/12/01	5	1 meter	800	1,600	2,400	203	21
		5	5 meters	620	1,900	2,900	231	18
	6/7/01	5	1 meter	100	1,200	1,800	233	24
		5	3 meters	200	1,200	2,100	266	22
		5	5 meters	200	1,200	1,300	286	29

Table 9: Total (TN:TP) and bioavailable (Inorganic-N:PO_4^{3-}) nitrogen and phosphorous ratios at Jackson, North Sterling and Prewitt Reservoirs from April through October 2001

	Jackson		Sterling		Prewitt	
	TN:TP	Inorg-N: PO_4^{3-}	TN:TP	Inorg-N: PO_4^{3-}	TN:TP	Inorg-N: PO_4^{3-}
4/10	23.7	na	22.9	Na	22.3	na
5/12	19.7	114.3	29.4	317.3	16.9	▨
6/7	12.9	54.2	22.5	▨	10.2	4.4
6/21	19.8	▨	62.3	▨	10.4	▨
7/5	12.7	14.5	33.3	168.8	9.2	3.4
7/19	12.0	**0.0 ***	17.3	▨	11.8	4.8
8/2	10.7	33.3	15.1	228.6	9.4	50.0
8/25	10.4	2.9	16.4	17.3	10.7	10.7
9/22	9.7	19.1	12.1	55.6	9.6	**0.0 ***
10/8	11.2	7.4	10.4	10.0	11.5	140.0
▨	PO_4^{3-} concentrations are less than the limiting concentration, 5 µg/L.					
*	Inorganic-N (Inorg-N) concentrations are less than the detection limit of 100 µg/L and potentially limiting at 20 µg/L.					

Total nutrient ratios (TN:TP) often ranged between 10 and 17, indicating that the reservoirs are co-limited. The reservoirs were co-limited between 50-60% of the time based upon total nutrient ratios. North Sterling Reservoir was phosphorous limited until early August, when the ratio using TN:TP was less than 17. Ratios using the bioavailable forms of the nutrients (inorganic-N:PO_4^{3-}) indicate that Jackson Reservoir is nitrogen limited on three days, phosphorous limited on five days and co-limited on one day. Using bioavailable nutrients (inorganic-N:PO_4^{3-}), North Sterling Reservoir was phosphorous limited from May through August, as well as September 22 and co-limited on August 25 and October 8. Prewitt Reservoir ratios using bioavailable nutrients suggested nitrogen limitation on four days, phosphorous limitation on four days and co-limitation on one day.

When considering both the nutrient ratios and concentrations, North Sterling Reservoir was phosphorous limited because the concentrations never decreased below potentially limiting values for inorganic nitrogen. However, the ratios decreased over the season to values suggesting co-limiting conditions. Bioavailable nutrients decrease below potentially limiting concentrations at both Jackson and Prewitt Reservoirs indicating that the reservoirs may be limited by both nitrogen and phosphorous at different times during the study period. Ratios also indicate nitrogen, phosphorous and co-limited conditions at Prewitt and Jackson Reservoirs. It is important to reiterate that for the majority of the time, the nutrients are present in sufficient quantities and although a ratio indicates limitation, neither nutrient may be limiting primary production.

Nutrients and Primary Production

Simple and multiple linear regression was used to evaluate relationships between nutrient concentrations and primary production, as measured by chlorophyll-*a*. Concentrations were transformed by using the logarithm of each value to normalize the data. The specific hypothesis tested is that there is a correlation between *log* nutrient concentration(s) and *log* chlorophyll-*a* concentration. The null hypothesis is that no correlation exists. The test statistic (α) is the type I error or the probability of observing a correlation when none exists. When the p-value is less than the designated α of 0.10 then the null hypothesis that there is no correlation between nutrient concentrations and chlorophyll-*a* is rejected and the relationship is deemed "significant". There was a significant positive relationship between *log* TP and *log* chlorophyll-*a* in North Sterling Reservoir ($r=0.73$, $p = 0.04$, $r^2=0.54$) based upon the analysis of 8 samples taken between June and October (Table 10) (Equation 1). This supports the hypothesis that TP and chlorophyll-*a* are positively correlated ($p = 0.04$). Approximately half of the variability in *log* chlorophyll-*a* was explained by the linear regression on *log* TP.

Table 10: Nutrient and chlorophyll-*a* correlation coefficient r and (p-value) at North Sterling, Prewitt and Jackson Reservoirs from June to October 2001

Reservoir	*log* TP	*log* TN	*log* PO_4^{3-}	*log* Inorg-N	*log* TP and *log* TN	*log* TP and *log* Inorg-N
North Sterling Reservoir	0.73 (0.04)	- 0.58 (0.13)	0.64 (0.09)	-0.88 (.004)	0.83 (0.05)	0.91 (0.01)
Prewitt Reservoir	0.52 (0.19)	0.34 (0.41)	0.47 (0.24)	0.12 (0.78)	0.78 (0.10)	0.53 (0.43)
Jackson Reservoir	0.77 (0.02)	0.65 (0.08)	0.76 (0.03)	0.13 (0.76)	0.82 (0.06)	0.78 (0.09)

Chlorophyll concentrations respond to increases in phosphorous concentrations.

Equation 1. *log* (chl-a) = 0.78 (*log* TP) + 0.04.

A negative correlation was observed between *log* inorganic-N and *log* chlorophyll-*a* (r =-0.88, p=0.004, r^2=0.77; n=8) (Equation 2). Approximately 77 percent of the variability in *log* chlorophyll-*a* concentrations is explained by the negative relationship with inorganic-N, chlorophyll-*a* concentrations increased with lower concentrations of inorganic-N. This reflects the observation that chlorophyll concentrations increased later in the season while inorganic-N concentrations decreased to below detectable limits. When *log* inorganic-N concentrations are zero, the predicted *log* chlorophyll-*a* value is 3.25.

Equation 2. *log*(chl-a) = -0.489 (*log* inorg-N) + 3.25

The hypothesized positive relationship between chlorophyll-*a* and TN was not significant at α=0.10 (p=0.13) at North Sterling Reservoir, thus the null hypothesis that no correlation exists is not rejected. The model with strongest correlation at North Sterling Reservoir used both TP and inorganic-N and explained 83% of the variability in chlorophyll-*a* (r = 0.91; p=0.01; r^2=0.83; n=8) (Equation 3). This equation reflects the seasonal decline in inorganic-N concentrations and positive relation with TP.

Equation 3. *log* (chl-a) = 2.24 + 0.32 (*log* TP) - 0.39 (*log* inorg-N)

From the 8 water quality samples collected at Prewitt Reservoir between June and October 2001, none of the hypothesized positive nutrient~chlorophyll-*a* relationships were significant at α = 0.10, leading to failure to reject the null hypothesis that no correlation exists. The greatest correlation coefficient using simple linear regression was between *log* TP and *log* chlorophyll-*a*. (r = 0.52; p = 0.19; r^2=0.27; n=8). When multiple regression was used with TP and TN the correlation was significant (p< α = 0.10) with the relationship explaining 61% of the variability in *log* chlorophyll-*a* concentrations (Equation 4). This equation also indicates that a decrease in *log* TN corresponds with an increase in *log* chlorophyll-*a* and both parameters had a p-value less than α =0.10, leading to a rejection of the null hypothesis that no correlation between TN and chlorophyll-*a* exists. The regression coefficients are higher than those at North Sterling Reservoir, reflecting the higher median chlorophyll-*a* concentrations at Prewitt Reservoir.

Equation 4. log (chl-a) = 2.80 + 3.88(log TP) –2.92(log TN)

At Jackson Reservoir significant relationships ($p < 0.10$) were found between chlorophyll-*a* and TP (p=0.02), TN (at p = 0.08) and PO_4^{3-} (p=0.03) leading to a rejection of the null hypothesis that no correlation exists between the nutrients and chlorophyll-*a* (Table 10). TP explains 59% of the variation in chlorophyll-*a* with a correlation coefficient of 0.77 (r=0.77; p = 0.02; $r^2 = .59$; n=8) (Figure 19) (Equation 5). Chlorophyll-*a* concentrations increase more than TP concentrations at Jackson Reservoir.

Equation 5. log (chl-a) = 1.70 (log TP) - 2.27.

The correlation between PO_4^{3-} and chlorophyll-*a* was similar to the TP relationship, describing 58% of the variation in chlorophyll-*a* (r = 0.76; p=0.03; r^2=0.58; n-8). The response ratio was less, indicating a 0.59 unit increase in chlorophyll-*a* per unit increase in PO_4^{3-}. Also, the intercept was positive (0.87) suggesting that even in the absence of PO_4^{3-}, the chlorophyll-*a* concentration would be 7.41 μg/L. Of the three reservoirs studied, only Jackson Reservoir showed a significant ($p<\alpha=0.10$) relationship between TN and chlorophyll-*a* (Equation 6); (r = 0.65; p = 0.08; r^2=0.42; n=8). The response ratio indicates that chlorophyll-*a* concentrations increase more than TN (1.80).

Equation 6. log (chl-a) = 1.80 (log TN) - 4.44

Multiple regression using both TP and TN explained the most variability in chlorophyll-*a* at Jackson Reservoir, 68% (p=0.06) (Equation 7). The *log* TN portion of the equation was negative indicating a decrease in *log* TN accompanies an associated increase in *log* chlorophyll-*a*. The coefficients are similar to those obtained at Prewitt Reservoir. On average, a one unit increase in *log* TP corresponds with a 3.55 unit increase in *log* chlorophyll-*a*.

Equation 7. log (chl-a) = 1.84 + 3.55(log TP) – 2.47(log TN)

SAS (SAS 1999) was used to test the TP~chlorophyll-*a* relationship by reservoir. The 'mixed' procedure (PROC MIXED) was used to test the analysis of variance for the mixed-effects model. The mixed effects model was used such that: *log* chlorophyll-*a* = reservoir * *log* (TP), to test for a reservoir effect with respect to *log*(TP). The random effects parameter, or random variable assumed to impact the model, was date. The *log* TP interaction between the three reservoirs was not significant, indicating that all three reservoirs are similar with respect to *log* TP. Equations were developed with a common slope for all three reservoirs, but the intercepts (or chlorophyll-*a* values) were different. Thus, using one equation to predict chlorophyll-*a* based on total phosphorous for all three reservoirs was not possible. However, the following three equations with a common slope, but different intercepts, were developed.

Equation 8. North Sterling Reservoir: log (chl-a) = -1.083 + 1.30 (log TP)

Equation 9. Prewitt Reservoir: log (chl-a) = -0.96 + 1.30 (log TP)

Equation 10. Jackson Reservoir: log (chl-a) = -1.3363 + 1.30 (log TP)

The common slope of 1.30 shows a greater increase in chlorophyll-*a* than in TP. The intercepts, all negative, indicate that no chlorophyll-*a* would be present without TP. The intercepts show that for the same concentration of TP, each reservoir will exhibit a different chlorophyll-*a* response. Prewitt Reservoir will have the highest chlorophyll-*a* concentration per unit TP and Jackson reservoir will have the lowest chlorophyll-*a* concentration. The significance of the equations was p=0.03 leading to a rejection of the null hypothesis than no correlation exists.

Several model selection methods were used to determine the best model and parameters to use at each reservoir. Forward selection looks for significance to move to a more complicated model while backwards selection considers lack of significance to move to a less complicated model. Stepwise selection considers the significance of previously added model variables to determine if the association can be dropped after the addition of the next variable. The best fitting subset regression equation, or Mallow's C_p, estimates the mean squared prediction errors to determine the parameters to produce the most accurate model (Ott and Longnecker 2001). At Jackson Reservoir all selection methods (forward, backwards, stepwise and Mallow's C_p) indicate that TP alone offers the best-fit model. Using Mallow's Cp at Jackson Reservoir the second model choice was PO_4^{3-} and the third uses both TP and PO_4^{3-}. At Prewitt Reservoir, TP and TN should be used to produce the best-fit chlorophyll-*a* model using backward elimination and Mallow's Cp. Forward and stepwise model selection methods did not meet the required significance of 0.10. Using Mallow's Cp at Prewitt Reservoir the second model choice was using TP alone and the third used TP, TN and Inorganic-N. At North Sterling Reservoir, inorganic-N was the best predictor using forward, backward and stepwise selection. However, Mallow's C_p method recommends using PO_4^{3-}, TN and inorganic-N for the best-fit model at North Sterling Reservoir. The second model choice was inorganic-N alone and the third incorporates both TP and inorganic-N.

Phytoplankton

Planktonic algae were identified to genus at each reservoir. No algae were found on the first two sampling days (April and May) with the first identifiable algae from a surface grab sample occurring in June. Some of the common chlorophyta (green algae) for all reservoirs include *Scenedesmus* and *Oocystis* (Table 11). The diatoms *Cyclotella* and *Nitzschia* were present at all three reservoirs. Cyanobacteria (blue-green algae)

Table 11: Algae genera identified at Jackson, Prewitt and North Sterling Reservoirs

		Sterling								Prewitt								Jackson							
Division	Genus	J	J	J	J	A	A	S	O	J	J	J	J	A	A	S	O	J	J	J	J	A	A	S	O
Cyanophyta	Agmellum													x											
	Anabena				x	x						x		x									x		
	Anacystis																					x			
	Aphanothece																					x			
	Aphanizomenon						x	x		x	x	x	x	x	x	x	x						x		
	Gomphosphaeria						x																		
	Merismopedia														x	x									
	Microcystis					x	x	x						x	x	x						x	x		X
	Oscillatoria						x	x	X					x	x	x		x		x				x	
	Pseudanabena	x	x							x	x							x							
	Spirulina																						x		
Euglenophyta	Entosiphon									x															
Cryptophyta	Kathablepharis	x								x															
	Goniomonas									x															X
Chrysophyta	Paraphysomonas		x																						
	Pedinella						x																		
	Synura						x																		
	Chrysochromulina	x																							
Bacillariophyta	Asterionella									x		x							x						
	Cyclotella	x					x	x						x	x						x	x		x	
	Fragilaria										x														
	Navicula													x	x	x		x					x	x	X
	Nitzschia	x					x							x		x		x				x		x	
	Pinnularia																			x					
	Stephanodiscus	x	x																	x				x	
	Synedra	x	x																						
	Tabellaria														x										
Chlorophyta	Actinastrum	x						x		x		x			x	x									
	Ankyra		x																						
	Chlamydomonas						x								x			x							
	Chlorella	x																							
	Chlorococcum							x																	
	Closterium										x														
	Coelastrum																	x							
	Cosmarium																	x			x				
	Dictyosphaerium	x	x																						
	Didymocystis	x																							
	Gonium																					x			
	Micractinium								X																
	Microsporum																	x							
	Nephrocytium																		x						
	Oocystis	x	x				x				x							x	x	x	x	x			
	Pediastrum	x	x				x							x				x					x		
	Scenedesmus	x	x				x			x	x			x	x				x	x		x	x	x	
	Selenastrum	x																x							
	Stigeoclonium																	x							
	Tetraselmis		x																						
	Tetraspora													x	x										
	Volvox					x																			

including *Aphanizomenon*, *Microcystis*, and *Anabena* were present. Although counts were not made, *Oocystis* was the dominant genus in the Jackson Reservoir sample on June 21. On August 2, *Aphanizomenon* and *Cyclotella* were common in the North Sterling Reservoir sample.

Cyanobacteria comprised a large portion of the phytoplankton population at different times over the study period. On August 25, *Aphanizomenon* was common at Prewitt Reservoir. An *Anabena flos-aquae* bloom occurred in mid-July at North Sterling Reservoir. A *Microcystis* bloom occurred at Jackson Reservoir on October 8, 2001.

Few phytoplankton from the Euglenophyta, Cryptophyta, or Chrysophyta Divisions were identified in the reservoirs and several of those found lack chlorophyll. Therefore, it can be assumed that these groups contribute minimally to the chlorophyll-*a*, *b* and *c* measurements. Chlorophyll-*a* is present in all of the three divisions remaining (Cyanophyta, Chlorophyta and Bacillariophyta). However, chlorophyll-*b* is only present in the Chlorophyta (green algae) and chlorophyll-*c* is only present in the Bacillariophyta (diatoms). Thus, we can relate increases in these chlorophyll concentrations with increases in group presence at the reservoirs. At North Sterling Reservoir, chlorophyll-*b* concentrations were greater than chlorophyll-*c* in July and September, indicating an increased presence of green algae (Figure 18). Between July and September, chlorophyll-*c* concentrations were higher suggesting an increase in diatoms. North Sterling Reservoir chlorophyll-*a* concentrations were less than those measured at the other two reservoirs, but continued to increase through October. Chlorophyll-*b* concentrations declined on the last sampling date.

Chlorophyll-*b* and -*c* measurements indicate that diatoms contributed more to chlorophyll concentrations than green algae in Prewitt Reservoir throughout the entire sampling period. Chlorophyll-*a* and -*c* followed a similar pattern while chlorophyll-*b* remained lower, with a maximum of 10 μg/L on August 25, 2001. All three chlorophyll concentrations peaked on August 25 and began to decline through the remainder of the study period. A chlorophyll peak occurred one month later at Jackson Reservoir (September 22, 2001). Jackson chlorophyll concentrations all increased from mid-July through September, with a decline in October. On August 25, chlorophyll-*c* concentrations were higher than chlorophyll-*b* at all reservoirs, suggesting diatoms were contributing more to the chlorophyll concentrations than green algae in late August.

No filling occurred between June 24 and September 24, 2001 at North Sterling Reservoir and 5 samples were taken within this time period. Although no inflows occurred from the South Platte River and the reservoir volume decreased by 90% during this time period, the TP concentrations increased and PO_4^{3-} concentrations fluctuated. TN and inorganic-N decreased (Figure 19).

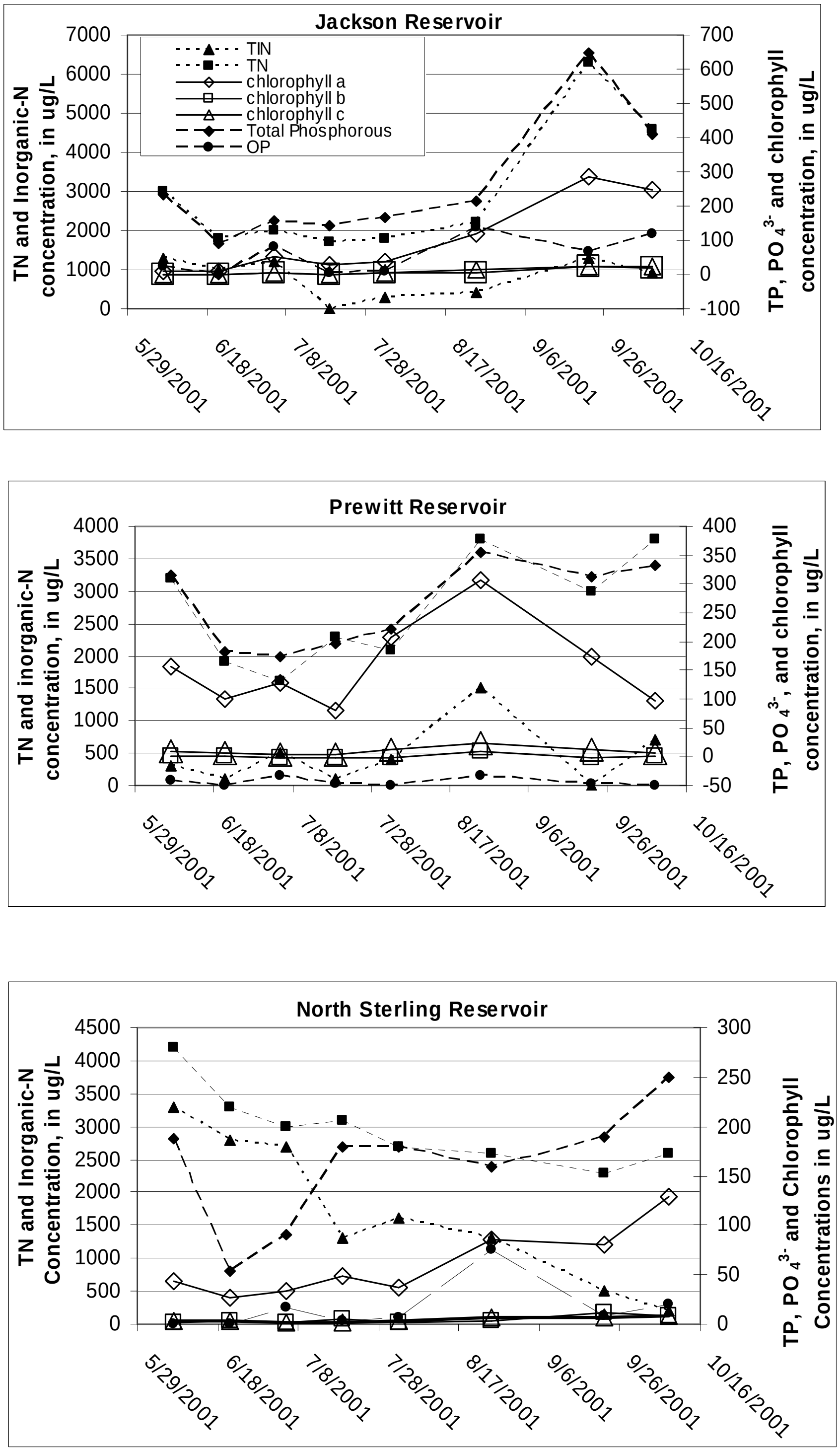

Figure 19. Nutrient and chlorophyll concentrations at Jackson, Prewitt and North Sterling Reservoirs between June and October 2001.

Filling at Prewitt Reservoir ended on July 14, but nutrient concentrations continued to increase through August 25. At North Sterling Reservoir there was a simultaneous increase in chlorophyll-*a* and TP. In general, all of the other nutrient concentrations declined over the study period, with the exception of an increase in PO_4^{3-}, which corresponded with an increase in chlorophyll-*a*.

Filling ended on April 20 at Jackson Reservoir. Concentrations of nitrogen and phosphorous decreased initially and then increased to the highest values on August 25. Chlorophyll-a concentrations at Jackson Reservoir generally followed the patterns of total nutrients and inorganic nitrogen. On the last sampling date, chlorophyll-a concentrations decreased while PO_4^{3-} concentrations increased. Two dips in chlorophyll-a correspond with dips in inorganic-N and PO_4^{3-} at Prewitt Reservoir. Chlorophyll-a concentrations decrease as inorganic-N and PO_4^{3-} concentrations decrease to below detection limits.

TSI and model spreadsheet results

A spreadsheet was developed to determine the trophic state of a reservoir or lake using three of the common computational methods, Carlson's TSI (1977), OECD fixed boundary system (OECD 1982) and EPA NES guidelines (USEPA 1974) . Vollenweider's plots (based upon phosphorous loading) and OECD Probability Plots are also included in this thesis to assess the trophic state of the reservoirs (Vollenweider 1976, OECD 1982).

On two days, Jackson Reservoir was classified as mesotrophic based upon chlorophyll-*a* using the EPA method. On all other days, the reservoirs were classified in the highest category available in the EPA method, eutrophic (Table 12). Based upon the OECD fixed boundary system all of the reservoirs were hypereutrophic for each parameter. The Carlson TSI reports the trophic state as a number from 0 to approximately 100 in an attempt to quantify trophic status and offer more than three descriptive categories for trophic state. Secchi disk depth was the least reliable with respect to the other measures, especially at Prewitt Reservoir, leading to the highest mean TSI (Figure 20). TP concentrations generally gave higher TSI than chlorophyll-*a* or Secchi disk depth in Jackson and Sterling Reservoirs. Chlorophyll-*a* gives the lowest TSI at all three reservoirs. Even though the TP concentrations were high, the primary production did not reach the same trophic classification levels. Most eutrophic lakes have TSI greater than 45 (Novotny and Olem 1994). The lowest value for any parameter and date was 50 indicating that by all measures the reservoirs are eutrophic based upon Carlson's TSI. Based upon an average of all the values, Prewitt showed the highest degree of eutrophication, followed by Jackson and Sterling Reservoirs, respectively.

Table 12: Trophic Status Index values for Jackson, Prewitt and North Sterling Reservoirs based upon 2001 nutrient, chlorophyll-*a* and Secchi disk measurements

Jackson Reservoir								
Carlson (1977)			U.S. EPA (1974)			OECD fixed boundary (1982)		
TP	Chl-a	SD	TP	Chl-a	SD	Metric	Value	Classification
83	50	67	E	M	E	Mean TP	258	H
69	50	66	E	M	E	Mean Chl-a	98	H
77	69	73	E	E	E	Peak Chl-a	285	H
76	63	67	E	E	E	Mean SD	0.49	H
78	66	71	E	E	E	Min SD	0.18	H
81	77	85	E	E	E			
98	86		E	E				
91	85		E	E				
Prewitt Reservoir								
Carlson (1977)			U.S. EPA (1974)			OECD fixed boundary (1982)		
TP	Chl-a	SD	TP	Chl-a	SD	Metric	Value	Classification
87	80	77	E	E	E	Mean TP	261	H
79	76	73	E	E	E	Mean Chl-a	156	H
78	78	79	E	E	E	Peak Chl-a	307	H
80	74	77	E	E	E	Mean SD	0.26	H
82	83	87	E	E	E	Min SD	0.15	H
89	87	85	E	E	E			
87	81	85	E	E	E			
88	75	78	E	E	E			
Sterling Reservoir								
Carlson (1977)			U.S. EPA (1974)			OECD fixed boundary (1982)		
TP	Chl-a	SD	TP	Chl-a	SD	Metric	Value	Classification
80	90	62	E	E	E	Mean TP	161	H
61	63	63	E	E	E	Mean Chl-a	109	H
69	65	62	E	E	E	Peak Chl-a	428	H
79	69	65	E	E	E	Mean SD	0.66	H
79	66	65	E	E	E	Min SD	0.37	H
77	74	71	E	E	E			
80	74	71	E	E	E			
84	78	75	E	E	E			

Key: O=oligotrophic, M=mesotrophic, E = eutrophic, H=hypereutrophic

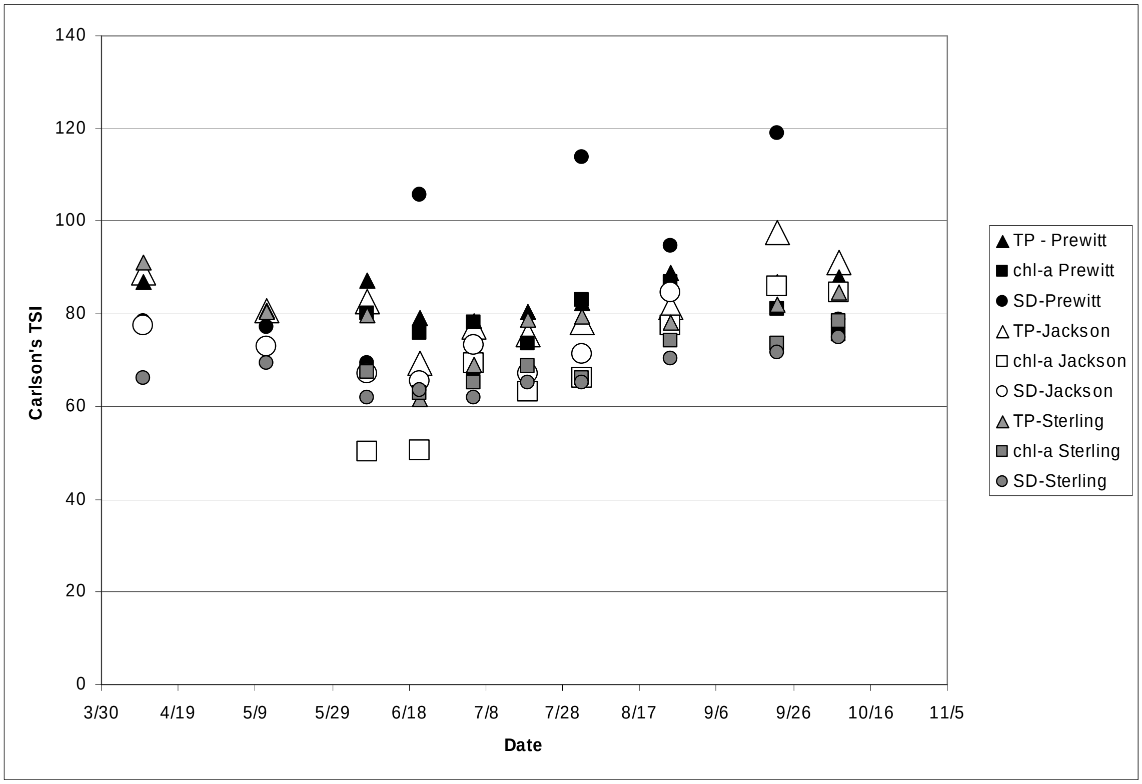

Figure 20. Carlson's TSI values for Jackson, Prewitt and North Sterling Reservoir based upon TP, chlorophyll-*a*, and Secchi depth (Carlson 1977).

Vollenweider plots (Figure 3) use the total input of phosphorous per year per surface area. Based upon the calculated incoming load estimated from mean South Platte River TP concentrations at Weldona in 2001, annual inflow, hydraulic residence time and maximum reservoir depth, all three reservoirs would be classified as eutrophic. The mean TP concentration (374 µg/L) was calculated using 3 samples collected in 2001 at Weldona, which is located between the Jackson and North Sterling Reservoir inlet canals (Sprague 2002). Residence time, defined as initial reservoir volume/total yearly outflow, was 0.84 years for Sterling, 2.4 years for Prewitt and 1.2 years for Jackson. The yearly area loading of TP was determined by multiplying the total inflow by the concentration and dividing this number by the initial reservoir surface area giving Sterling (4.34 g TP/m^2/yr), Prewitt (2.78 g TP/m^2/yr) and Jackson (1.01 g TP/ m^2/ yr). The calculated values are used along with mean depth to determine the trophic state using the plot (Figure 3). Since the mean depth was not available, the maximum depth was used as a conservative measure. Using the maximum depth on the x-axis (depth / residence time) will produce a higher value for the horizontal axis, making the potential classification more likely lower on the trophic scale. Estimation based upon Vollenweider plots is approximate because the incoming TP was estimated from South Platte River mean concentrations, the surface area and depth are approximate and they fluctuate seasonally.

The incoming phosphorous loads indicate that regardless of the depth or residence time, the reservoirs are classified as eutrophic.

Using the OECD probability plot, North Sterling, Prewitt and Jackson Reservoir concentrations were beyond the greatest value and are therefore considered hypereutrophic based upon TP concentrations (Figure 4). North Sterling had a 10% probability of being eutrophic and 90% probability of being hypereutrophic based upon mean chlorophyll-*a*. Jackson had a 5% probability of being eutrophic with a 95% probability of being hypereutrophic based upon chlorophyll-*a* concentrations. Prewitt reservoir chlorophyll-*a* concentrations were greater than the largest value on the graph leading to a 100% probability of hypereutrophic conditions based upon chlorophyll-*a*.

A spreadsheet with common nutrient~chlorophyll-*a* models was developed which allows input of observed values and reports five measures of precision for the input data (See methods). This spreadsheet was used to evaluate the models given the data from 8 sampling days at the reservoirs.

In evaluating the measures of precision at North Sterling Reservoir, an equation using both TN and total phosphorus had the best correlation coefficient between measured and predicted *log* chlorophyll-*a* values (0.82) and the lowest percent error (38.2%); (Smith 1982); (Table 13). A different equation, developed for nutrient balanced lakes, had the lowest average error (59.8) (Brezonik 1984). The correlation coefficient using untransformed values was also best for a TP and TN mixed model (Canfield Jr. 1983). The smallest 95% confidence interval was 28-120% based upon a TP model developed for Florida lakes (Baker et al. 1981).

In contrast with North Sterling Reservoir, the best models for Prewitt Reservoir, based upon correlation coefficients between measured and predicted chlorophyll, were models based upon TP alone (r=0.52); (Table 14). The smallest confidence interval was 33 - 71 % for the calculated chlorophyll. The smallest average error and percentage error was found using an equation developed by Brown (2000).

At Jackson Reservoir the highest correlation coefficient between predicted and measured log chlorophyll-*a* values was based upon TP (r=0.77); (Table 15). The untransformed values yielded the best correlation of r = 0.92 using TP models. The lowest average error was 35.30 based upon an equation for nitrogen limited lakes using TN (Brezonik 1984). The smallest percent (70.5%) error was found for Carlson's total phosphorus equation (Carlson, 1977), however it produced a large average error and 95% confidence interval. Similar to North Sterling Reservoir, the smallest 95% confidence interval was between 27-231 % using the model developed by Baker (Baker et al. 1981).

Table 13: Correlation coefficient, confidence interval, average error and percentage error between predicted and measured chlorophyll-a concentrations at North Sterling Reservoir in 2001

Results						calculated chlorophyll	
Equation	**Using**	**r - log values**	**r - actual values**	**lower confidence limit**	**upper confidence limit**	**average error**	**percent error**
Carlson	TP	0.62	0.36	31	911	98	60
Brown	TP	0.62	0.37	52	217	62	56
Brown	TN	0.36	0.73	39	214	73	65
Brown	TP & TN	0.68	0.52	58	226	68	77
Brown	TP	0.59	0.37	47	210	62	48
Dillon & Ringer	TP	0.62	0.36	56	241	83	91
Jones & Bachman	TP	0.62	0.36	60	260	97	118
Hoyer	TP	0.62	0.36	52	218	65	61
Canfield	TP	0.62	0.37	33	141	78	51
Huber	TP	0.62	0.36	69	301	137	193
Baker	TP	0.62	0.37	28	120	88	66
Lambou	TP	0.62	0.37	27	119	89	68
Canfield	TN	0.36	0.74	41	220	73	71
Hoyer	TN	0.36	0.70	31	173	77	47
Smith	TP & TN	0.82	0.89	36	157	72	38
Canfield	TP & TN	0.75	0.90	43	197	69	55
Hoyer	TP & TN	0.64	0.43	57	227	72	77
Canfield	TP	0.62	0.37	55	227	70	71
Canfield	TN	0.36	0.72	40	219	73	68
Canfield	TP & TN	0.81	0.80	56	233	65	82
Brezonik	TP	0.62	0.35	51	1676	178	268
Brezonik	TN	0.36	0.74	19	946	74	110
Brezonik	TP	0.62	0.37	15	399	60	41
Brezonik	TN	0.36	0.74	16	769	73	74

Table 14: Correlation coefficient, confidence interval, average error and percentage error between predicted and measured chlorophyll-*a* concentrations at Prewitt Reservoir in 2001

Results				calculated chlorophyll			
Equation	**Using**	**r - log values**	**r - actual values**	**lower confidence limit**	**upper confidence limit**	**average error**	**percent error**
Carlson	TP	0.52	0.54	68	492	126	41
Brown	TP	0.52	0.54	68	148	46	32
Brown	TN	0.34	0.41	39	103	103	61
Brown	TP & TN	0.47	0.51	67	157	51	37
Brown	TP	0.46	0.43	53	124	69	35
Dillon & Ringer	TP	0.52	0.54	78	184	85	69
Jones & Bachman	TP	0.52	0.54	84	199	124	98
Hoyer	TP	0.52	0.54	70	158	53	40
Canfield	TP	0.52	0.54	41	87	112	68
Huber	TP	0.52	0.55	97	235	246	183
Baker	TP	0.52	0.54	35	75	125	77
Lambou	TP	0.52	0.53	33	71	129	80
Canfield	TN	0.34	0.41	39	108	99	58
Hoyer	TN	0.34	0.41	34	80	124	76
Smith	TP & TN	0.39	0.45	36	92	113	69
Canfield	TP & TN	0.38	0.44	42	111	92	54
Hoyer	TP & TN	0.50	0.53	72	168	59	48
Canfield	TP	0.52	0.54	72	157	53	40
Canfield	TN	0.34	0.41	40	104	100	59
Canfield	TP & TN	0.42	0.47	58	144	55	35
Brezonik	TP	0.52	0.55	122	1004	395	285
Brezonik	TN	0.34	0.41	16	191	79	48
Brezonik	TP	0.52	0.53	30	196	55	33
Brezonik	TN	0.34	0.41	80	845	96	57

Table 15: Correlation coefficient, confidence interval, average error and percentage error between predicted and measured chlorophyll-a concentrations at Jackson Reservoir in 2001

Results						calculated chlorophyll	
Equation	**Using**	**r - log values**	**r - actual values**	**lower confidence limit**	**upper confidence limit**	**average error**	**percent error**
Carlson	TP	0.77	0.90	52	3692	210	70
Brown	TP	0.77	0.92	55	411	53	337
Brown	TN	0.63	0.90	33	318	58	156
Brown	TP & TN	0.74	0.91	57	423	71	375
Brown	TP	0.27	0.08	31	485	81	277
Dillon & Ringer	TP	0.77	0.90	70	443	158	500
Jones & Bachma	TP	0.77	0.90	75	477	209	614
Hoyer	TP	0.77	0.91	60	407	78	364
Canfield	TP	0.77	0.92	30	274	67	111
Huber	TP	0.77	0.90	88	551	350	907
Baker	TP	0.77	0.92	27	231	74	92
Lambou	TP	0.77	0.92	24	232	78	90
Canfield	TN	0.63	0.90	34	319	52	162
Hoyer	TN	0.63	0.90	25	278	75	116
Smith	TP & TN	0.69	0.91	31	263	62	120
Canfield	TP & TN	0.67	0.90	37	319	48	163
Hoyer	TP & TN	0.76	0.91	63	426	105	419
Canfield	TP	0.77	0.92	59	430	75	393
Canfield	TN	0.63	0.90	34	327	57	164
Canfield	TP & TN	0.71	0.91	50	409	47	314
Brezonik	TP	0.77	0.90	101	6608	538	1232
Brezonik	TN	0.63	0.90	13	2152	35	239
Brezonik	TP	0.77	0.90	21	1665	41	221
Brezonik	TN	0.63	0.90	7	1114	51	168

DISCUSSION

Nutrient concentrations, trends, and ratios and changes in dissolved oxygen and temperature are evaluated. Nutrient-chlorophyll relationships, and the applicability of trophic state indices and models, are evaluated and discussed. The applicability and function of trophic indices and models to South Platte River off-channel reservoirs is addressed.

Comparison of reservoir nutrient data from 1995 and 2001

In 1995 the USGS NAWQA program conducted a reservoir synoptic study on Riverside, Jackson, Prewitt, North Sterling and Jumbo Reservoirs (USGS 1995b). The study collected nutrient samples on four days and chlorophyll-*a* samples on three days. Samples were collected at approximately the same sites for the 1995 and 2001 studies, preserved on ice during transport and analyzed using similar laboratory methods (Appendix B) (Sprague, 2002, Kimborough, 2002).

Since the USGS samples are from only three days from May through September, median values were used to compare the two data sets (Table 16). Ammonium and TKN were less in 1995 than 2001 for all three reservoirs. Jackson Reservoir chlorophyll-*a*, PO_4^{3-} and TP were greater in 1995 than 2001. All measurements, except nitrate, were less in 1995 than 2001 at North Sterling Reservoir. Concentrations were different between years, however they were not expected to be similar due to differences in water uses, water yield, and period of sampling.

Nitrate concentrations in all three reservoirs decreased over time in both 1995 and 2001 (Figure 21). In general, the highest concentrations were measured in March and April and decreased to below detection in September. Prewitt Reservoir in 2001 was the exception, with concentrations fluctuating between 1,400 μg/L and detection limits. Nitrate concentrations began to increase again in October in Jackson and Prewitt Reservoirs in 2001.

Total and bioavailable nutrient concentrations and ratios were analyzed to determine the potential limiting nutrient in both years. Nutrient concentrations must be evaluated in conjunction with ratios since nutrients may be present in sufficient quantities that neither limits primary production, even if a ratio indicates limitation. Ratios below 10 indicate nitrogen limitation and ratios above 17 suggest phosphorous limitation (Ryding and Rast 1989). Values between 10 and 17 indicate co-limitation, or that growth is limited by both nitrogen and phosphorous. Concentrations of PO_4^{3-} below 5 μg/L indicate that phosphorous may be limiting while concentrations of inorganic-N less than 20 μg/L indicate nitrogen limitation (Ryding and Rast 1989). The inorganic-N detection limit for the 1995 study was 50μg/L (nitrate & nitrite) and 15 μg/L (ammonium).

Table16. Median nutrient and chlorophyll concentrations at Jackson, Prewitt and North Sterling Reservoirs in 1995 and 2001

	Jackson		**Prewitt**		**Sterling**	
	1995	2001	1995	2001	1995	2001
Chlorophyll-*a* (μg/L)	53	45	23	142	26	46
Chlorophyll-*b* (μg/L)	0.1	3.35	1.1	0.1	1.4	3.6
NH_4-N (μg/L)	25	400	0	200	50	300
Nitrate (μg/L)	410	500	275	100	1,840	1,650
Nitrite (μg/L)	25	100	0	0	60	100
TKN (μg/L)	1,900	1,950	1,300	3,000	1,100	1,800
PO_4^{3-} (μg/L)	50	24	0	16	0	9
TP (μg/L)	190	91	70	267	120	183

The detection limit for all forms of nitrogen in the 2001 study was 100 μg/L. Any measurement below this detection limit is potentially limiting. PO_4^{3-} was below 5 μg/L on various dates at all three reservoirs in both years. Inorganic-N was below 100 μg/L in September at Sterling (1995), Prewitt (1995 and 2001) and Jackson (1995). TN:TP ratios in 2001 ranged from 24 to 10 at Jackson, 23 to 9 at Prewitt, and 62 to 10 at Sterling

The detection limit for all forms of nitrogen in the 2001 study was 100 suggesting co- and phosphorous limitation. In 1995 inorganic-NN: PO_4^{3-} ratios at Jackson Reservoir decreased, indicating phosphorous limitation on the first two sampling days (60 and 29) and nitrogen limitation on the last two days (1.6 and 0.1).

The nutrient concentrations and ratios indicated co-limitation at Prewitt and Jackson Reservoirs. North Sterling Reservoir was initially phosphorous limited in both years, but ratios or concentrations indicate co-limitation by September.

The TSI models indicated that the reservoirs were eutrophic or hypereutrophic. Secchi disk measurements for 1995 were not specifically reported, however since near surface samples were taken at twice the Secchi disk depth, the Secchi disk depth was assumed to be half of the sampling depth (Sprague, written communication, 2002). The TSI index values increased from June through the end of the summer for both studies. The Carlson TSI (Carlson 1977) can be calculated separately based upon TP, chlorophyll-*a* and Secchi disk depth. The Carlson TSI values were higher based upon TP than chlorophyll-*a* at all three reservoirs for both years.

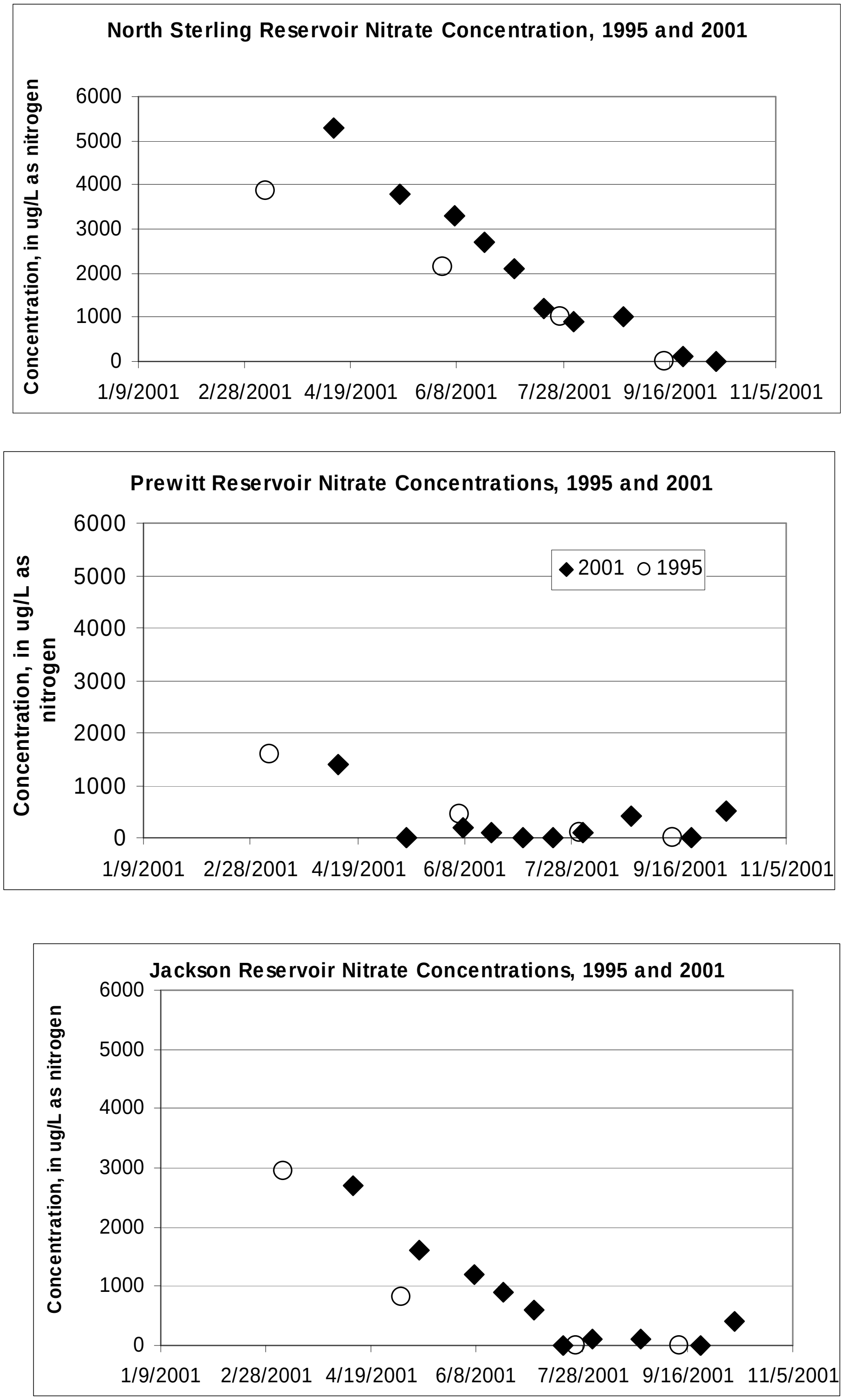

Figure 21. Nitrate concentrations between May and October in Jackson, North Sterling and Prewitt Reservoirs in 1995 (USGS) and 2001 (this study)

In 1995 and 2001, the EPA method (EPA 1974) classified all reservoirs as eutrophic based upon TP and Secchi depth. In 1995, the earliest chlorophyll-*a* measurements, collected in late May and early June, resulted in oligotrophic classifications at Jackson and Prewitt Reservoirs. Similarly, the lowest classification in 2001 was based upon the earliest chlorophyll-*a* measurement in Jackson reservoir. This indicates that although TP concentrations are within the eutrophic or hypereutrophic range, primary production is not as high early in the season. By July of both years all of the reservoirs were classified as eutrophic by all measures.

The OECD fixed boundary system (OECD 1982) uses mean chlorophyll-*a*, Secchi disk depth and TP, as well as peak chlorophyll-*a* and minimum Secchi depth. Based upon the OECD fixed boundary system, Secchi depth indicated that all three reservoirs were hypereutrophic in 1995 and 2001. TP and chlorophyll-*a* models classified all reservoirs as hypereutrophic in 2001. TP and chlorophyll-*a* levels in 1995 suggested both eutrophic or hypereutrophic conditions at the reservoirs.

The remainder of the discussion will focus on data collected in 2001, unless otherwise indicated.

Physical Parameters

In 2001, more sampling days at North Sterling Reservoir had no change (defined as 1°C or less) from the reservoir surface to maximum depth than at Jackson Reservoir; 56% of the sampling days water temperature did not decline by less than 1°C. In contrast, only 17% of the depth profile measurements at Jackson Reservoir showed a change of less than 1°C from the reservoir surface to maximum depth. North Sterling Reservoir was sampled in the morning and Jackson Reservoir was sampled in the afternoon on each sampling date. It may be possible that the lack of temperature change with depth at North Sterling Reservoir was a result of sample collection timing. In general, mean water temperature from 0 - 3 meters in depth was between 0.4 - 2.9 °C higher at Jackson Reservoir than North Sterling Reservoir. However, the within lake variation between the mean temperature between 0-3 meters at the three sample sites at each reservoir was between 0.3 - 2.4 °C. The greatest difference in mean water temperature between North Sterling and Jackson Reservoirs was only 0.5 °C more than the greatest difference in water temperature within the reservoirs, suggesting than sample timing may not have had a significant affect on reservoir water temperature.

In general, dissolved oxygen concentrations decreased with depth at North Sterling and Jackson Reservoirs, occasionally decreasing to anoxic conditions (less than 1 mg/L). This decline is typical of eutrophic reservoirs. A similar decrease was found in another eutrophic plains lake (Wang et al. 1999). The saturation oxygen content of water is greater at lower temperatures, leading to expected higher dissolved oxygen concentrations with depth based upon temperature alone at Jackson Reservoir, where the temperature decreases with depth. However, dissolved oxygen concentrations decreased with depth. Several processes affect dissolved oxygen concentrations in lakes and reservoirs. Biological activity (photosynthesis) near reservoir surface and wind can increase the dissolved oxygen concentrations during the day. Decomposition of organic matter may contribute to a decreases in dissolved oxygen concentrations in the hypolimnion (Heinonen et al. 2000).

Dissolved oxygen concentrations in warm water should be greater than 5 mg/L to protect aquatic communities (Welch 1992). Depth profiles show dissolved oxygen concentrations below 5 mg/L on 6 of 7 sampling days at North Sterling Reservoir and 4 of 5 at Jackson Reservoir. Dissolved oxygen concentrations from the reservoir surface to maximum depth varied between the sample sites on each sampling day, suggesting different oxygen declines with depth at different sampling sites on each day. The rate of oxygen depletion at the bottom of the reservoir has been used to indicate the amount of primary production in a lake or reservoir and predictions of oxygen concentrations in the hypolimnion have been linked with TP, chlorophyll-*a* and Secchi disk depth (Walker 1979).

Reservoir water quality

Reservoir nutrient and chlorophyll concentrations

Nutrient and chlorophyll concentrations measured in Jackson, Prewitt and North Sterling Reservoirs in 2001 exceed EPA recommended numeric values for reservoirs in Ecoregion V (Table 3). The minimum TP measurement in 2001 was almost twice the recommended maximum concentration of 33 μg/L. The median TP measurements at Jackson, Prewitt and North Sterling Reservoirs were between 4 and 8 times greater than the recommended standard; median values were 208, 267 and 138 μg/L, respectively.

TN is the summation of TKN, nitrate and nitrite. The EPA recommends a maximum concentration of TN of 560 μg/L in reservoirs in Ecoregion V. The median TN concentrations were at least 4 times greater than recommended levels with concentrations of 2,550, 3,100 and 3,550 μg/L at Jackson, Prewitt and Sterling, respectively.

Chlorophyll-*a* concentrations at Jackson, Prewitt and North Sterling Reservoirs also exceeded the recommended level of 2.33 μg/L with the smallest measurement being 7 μg/L early in the season at Jackson Reservoir. The median values at Jackson and North Sterling were similar, 45 and 46 μg/L, respectively. The median value at Prewitt Reservoir was approximately 3 times larger, 142 μg/L.

During the period of no inflows from the South Platte River, the TP concentrations increased in all three reservoirs. Phosphorous is typically bound to sediment, but at low dissolved oxygen concentrations (<0.5 mg/L) phosphorous can become soluble in water (Heinonen 2000). Since dissolved oxygen concentrations decreased to below 0.5 mg/L in June and July at North Sterling and Jackson Reservoirs it is possible that the sediment is a source of additional phosphorous. As discussed in the following section, this dissolved oxygen decline may also affect the nitrogen species found in the water.

Nutrient Trends

Initial nitrate concentrations of between 1,400 and 5,300 μg/L decreased to below detection limits at Jackson and North Sterling Reservoirs, respectively. When dissolved oxygen decreases in the hypolimnion, denitrification can occur increasing levels of ammonia and nitrogen gas (Heinonen, 2000). In eutrophic or hypereutrophic lakes with low oxygen concentrations in the hypolimnion, most of the nitrate is reduced to nitrogen gas (Bronmark and Hansson 1998). Decreases in nitrogen could also be due to biological use by algae. A similar nitrate trend (from 5,000 μg/L to below detection limits) was found in shallow ponds in England (Bennion and Smith, 2000). A rapid decline in nitrate, attributed to algal assimilation and denitrification, was observed elsewhere (Wetzel 2001). In another plains reservoir, nitrate concentrations showed a decline from 500 μg/L to 10 μg/L between May and August 1997. By December, this decline had stopped and nitrate concentrations increased to their highest levels (Wang et al. 1999). Thus, it is possible that the greatest nitrate concentrations in Jackson, Prewitt and North Sterling Reservoirs would be observed in the winter, however this has not been confirmed since both the 1995 and 2001 study periods were from March or April through October.

A study on nitrate retention in phosphorous limited lakes shows it to be independent of chlorophyll-*a* concentrations, suggesting that algal assimilation is less important than bacterial denitrification in the nitrate removal process (Prairie and Langevin 1990). Since North Sterling Reservoir was PO_4^{3-} limited according to concentrations (<5μg/L) in June 2001 and much of the 1995 study period, it is likely that bacterial denitrification plays a significant role in nitrate removal. PO_4^{3-} concentrations below 5μg/L were also observed at Prewitt (several days) and Jackson (1 day) in 1995 and 2001, indicating that bacterial denitrification was a potential source of nitrate removal in all three reservoirs.

Studies have found that lower lake levels are followed by higher TP concentrations (Berman 1997). Increases in TP concentrations occurred in all three reservoirs after reservoir inflows no longer occurred. Reservoir volume and depth decreased at all three of the reservoirs between June and September leaving a portion of the lake sediments exposed. Drying of lake sediments can increase the amount of phosphate released from sediments from 0.9 to 38.2 μg/g of dry sediment (Klotz and Linn 2001). Thus, internal phosphorous loading in lakes may be influenced by lake draw down. Another source of additional phosphate in the water without inflow could be PO_4^{3-} bound to submerged lake sediments. At pH values higher than 8, PO_4^{3-} becomes soluble in water. The pH was above 8 at all three reservoirs when TP peaks occurred. Increases of phosphorous concentrations in the water of eutrophic lakes may be a cyclic internal process; primary production increases the pH of the water, which promotes phosphorous release, which in turn increases primary production (Bronmark and Hansson 1998).

Chlorophyll-*a* concentrations increased to their maxima at different times during the study period. The median was used in analysis since chlorophyll-*a* and nutrient concentrations are not normally distributed. Chlorophyll-*a* concentrations were between

45 and 142 μg/L with relatively high median TP (91 - 267 μg/L). A study on saline lakes with high TP concentrations (2,000 - 13,000 μg/L) found low chlorophyll-*a* concentrations (3 - 10 μg/L) (Campbell and Prepas 1986). The study found that inorganic nitrogen limited algal growth and suggested that nitrogen cycling may be different in saline lakes. The saline lakes had total dissolved solids of greater than 5,000 mg/L, which is 5 times the concentration at the South Platte River Reservoirs. The association between salinity and nitrogen cycling limitation is an area of future study.

Nutrient Ratios

In reservoirs along the South Platte River, bioavailable nutrients decreased to limiting concentrations for PO_4^{3-} at all three reservoirs and for inorganic-N at Prewitt and Jackson Reservoir. Nitrate concentrations were below detection in the fall of 1995 and at Prewitt in 2001. N:P ratios also typically decreased over the season. The concentrations and ratios indicate that both nitrogen and phosphorous are limiting during parts of the season. Based upon nutrient concentrations, the reservoirs are phosphorous limited in 22% of the samples and inorganic-N limited in 7% of the samples. Concentrations indicate that neither nutrient limits algal growth during 71% of the study period. Another study of eight Colorado lakes showed that the lakes are primarily nitrogen limited or co-limited, with phosphorous limitation comprising only 21% of all observed cases of limitation (Morris and Lewis 1988). The study examined *in situ* nutrient enrichment experiments and found that 57% of the containers showed no limitation, as compared with 71% determined in the South Platte Reservoirs in 2001 (this study). Of the 43% showing some form of limitation, nitrogen alone or in combination with phosphorous accounted for 79% of all cases of limitation. The Colorado lakes study also found periods of limitation frequently interrupted by periods of nutrient sufficiency (Morris and Lewis 1988). An analysis of the N:P ratio in a plains reservoir in central Kansas shows the lake as nitrogen or co-limited during most of the year and a TN decrease during the productive season (Wang, 1999). The low N:P ratios and decline in inorganic-N observed in Sterling, Jackson, and Prewitt Reservoirs may have effects on the algae genera present, primary production and reservoir management.

Phytoplankton

Nutrient ratios may also indicate a change in reservoir productivity in both quantity and composition (Ryding and Rast 1989, Novotny and Olem 1994, Levich 1996, Bulgakov and Levich 1999, Smith and Bennett 1999, Graham and Wilcox 2000). The seasonal change in the ratio could have changed reservoir alga composition. Green algae may be more common in the spring and cyanobacteria that are able to fix atmospheric nitrogen may increase in the late summer and early fall. Several studies have found that a decreasing N:P ratio and increasing nitrogen deficiency have lead to cyanobacterial blooming (Levich 1996, Smith 1995, Gophen, 1999). One study found that the nutrient conditions favorable for cyanobacterial blooms increased over the past 20 years (Smith 1995).

A bloom of *Anabena* occurred at North Sterling Reservoir on July 19, 2001 and a *Microcystis* bloom occurred at Jackson Reservoir on October 8, 2001. Inorganic-N concentrations were higher that values considered limiting (20 μg/L), with concentrations of 1,300 μg/L and 900 μg/L, respectively.

PO_4^{3-} at Sterling during the *Anabena* bloom was 3 μg/L, which is less than the level considered limiting, indicating that bioavailable phosphorous control may not minimize one of the most ecologically harmful results of eutrophication, specifically cyanobacterial blooms. During the bloom, clumps of *Anabena* were visible in North Sterling Reservoir and none were collected in the sample for water quality analysis. It is possible that the algae were quickly taking up the reservoir PO_4^{3-}, resulting in the low concentrations in the ambient water.

PO_4^{3-} concentration at Jackson was 121 μg/L, providing sufficient bioavailable nitrogen and phosphorous for phytoplankton growth. *Microcystis* is non-heterocystis and unable to fix nitrogen, therefore it does not have a competitive advantage during low environmental nitrogen concentrations (Oliver and Ganf 2000). However, limited nitrogen supply has been shown favorable to *Microcystis* (Bulgakov and Levich 1999). As seen in 2001, cyanobacterial blooms could not be linked to nutrient ratios or concentrations, and contrary to convention, a cyanobacterial bloom occurred in conjunction with low bioavailable phosphorous concentrations. It is possible that bioavailable phosphorous was being utilized by the cyanobacteria, thus resulting in low ambient concentrations. Others refute the hypothesis that nutrient ratios can regulate phytoplankton community composition (Reynolds 1999).

Nutrient addition experiments at Cherry Creek Reservoir in 1992 showed that although both were limiting phytoplankton growth, nitrogen addition increased growth by a factor of six without phosphorous addition (Knowlton and Jones 1996). The study suggests that Cherry Creek Reservoir is nitrogen limited, however nitrogen fixing cyanobacterial blooms rarely occur. Thus, although conditions offering a competitive advantage to nitrogen fixing algae exist, specifically the presence of sufficient supplies of phosphorous, blooms do not occur.

Nutrients and Primary Production

Based upon linear regression with the 2001 data, there was a relationship between TP and chlorophyll-*a* at North Sterling ($r=0.73$; $p=0.04$) and Jackson Reservoir ($r=0.77$; $p=0.02$). Nitrogen was related to chlorophyll-*a* at North Sterling ($r=-0.88$; $p=0.004$) and Jackson ($r=0.65$; $p=0.08$) in inorganic and total forms, respectively. However, rather than the hypothesized positive correlation between inorganic nitrogen and chlorophyll-*a*, a negative correlation was found indicating an increase in chlorophyll-*a* while inorganic nitrogen decreased. A negative correlation between ammonium, one of the components of inorganic nitrogen, and chlorophyll-a was found (Perkins and Underwood 2000). The use of TN and TP in multiple regression improved the correlation at all three reservoirs, however the strongest correlation at North Sterling Reservoir was obtained using inorganic-N and TP in multiple regression (r=0.91; p=0.01). The strengthened correlation (when using nitrogen) is accomplished not by the addition of a nitrogen factor, but by subtracting the nitrogen component of the equation reflecting the finding that nitrogen decreases over the study period.

The sample size of eight measurements from one year may not afford the power to develop equations intended to represent the reservoirs in future years or predictions. Instead we could use the measured values with additional data or determine an existing equation developed from a larger data set to apply to a particular locale.

An assumption that phosphorous controls primary production is the basis for the expected correlation between TP and chlorophyll-*a*. A study of Cherry Creek Reservoir found that phosphorous concentrations were sufficient to supply a larger chlorophyll-*a* concentration typically observed (Knowlton and Jones 1996).

TN can also influence chlorophyll concentrations, especially when TP concentrations are elevated (Smith 1982, Brown et al. 2000). In South Platte off-channel storage reservoirs during 2001, the linear regression on the log of TP alone explained approximately 50% of the variability in chlorophyll-*a* in both North Sterling and Jackson Reservoirs. The TP~chlorophyll-*a* relationship in Prewitt Reservoir was not significant.

Several studies have confirmed the sigmoidal TP~chlorophyll-*a* relationship and show that the slope of the regression line decreases above 100 μg/L (Brown, 2000; Smith 1982). Phytoplankton biomass has been show to be proportional to nutrients up to a point when additional nutrients cause no further increase in algal growth (Ryding and Rast 1989). The median TP concentration at North Sterling, Jackson and Prewitt Reservoirs was greater that 100 μg/L. Factors other than TP influence primary production at concentrations of TP this high (Brown 2000). Brown found a linear relationship for concentrations of TP up to 160 μg/L. In 2001, only 10% of the samples collected had TP levels below 160 μg/L. The linear model works well for concentrations less than 160 μg/L. Therefore, it is possible that the TP~chlorophyll-*a* relationship for these high total phosphorous concentrations may be better described by a non-linear model.

In 2001, one of the factors contributing to primary production, given the high TP concentrations, is TN and Inorganic-N. The addition of TN to the TP regression at all three reservoirs improved the nutrient~chlorophyll-*a* relationship, explaining between 60 and 70% of the variability, making the regression at Prewitt Reservoir significant (α=0.10) and yielding the strongest equations for Prewitt and Jackson Reservoirs. Rather than TN, the addition of inorganic-N to the equation leads to the strongest equation at North Sterling Reservoir (r^2=.83).

The coefficient of determination (r^2=0.54 and 0.60) for South Platte Reservoirs based upon TP, was less than others previously obtained (i.e., Brown (2000) r^2 = .75). The data analyzed by Brown were paired annual mean data rather than paired measurement from April - October in this study. The study using paired annual mean data would be subject to the effects of data aggregation, specifically that relations between chlorophyll-*a* and TP will be stronger (Jones et al. 1998).

Further examination of the equation derived for North Sterling reservoir indicates a negative correlation between inorganic nitrogen and chlorophyll-*a* indicating an increase in chlorophyll-*a* while inorganic nitrogen concentrations decreased. Studies have found that algae utilize ammonium, nitrate and free nitrogen in preferential order (Wetzel 2001). Environmental levels of ammonium and nitrate regulate nitrogen fixation. When a decrease in nitrate concentrations in the reservoirs to detection limits is accompanied by ammonium concentrations below detection limits, this may afford a competitive advantage to nitrogen fixing cyanobacteria. Nitrate and ammonium concentrations decreased to below these limits at Sterling in October, Prewitt on mid-July and September and Jackson in late July. Similar to findings at Cherry Creek Reservoir, the low nitrate and ammonium levels did not coincide with cyanobacterial blooms (Knowlton and Jones 1996).

TSI and model utilization

Several factors limit the use of TSI: nitrogen limitation, mean concentration utilization and limited classification categories. Nitrogen limitation hinders the utility of models based solely on TP. Although a nitrate decline was previously described, the EPA model does not account for that because it relies on mean nutrient concentrations. The use of the OECD fixed boundary system or the EPA fixed boundary system provided terminology to describe the trophic state of the reservoirs, but only offered between 3 and 5 options (ultraoligotrophic, oligotrophic, mesotrophic, eutrophic and hypereutrophic) for describing the reservoirs. In 2001, the reservoirs (excluding Jackson Reservoir chlorophyll-*a* for the first two sampling days) were generally in the highest classification based upon each parameter. The chlorophyll-*a* concentrations did not lead to a trophic classification as high as the other parameters. It is clear from the indices that the reservoirs are eutrophic or hypereutrophic, but little other information is provided from the indices. For example, the mean TP concentration at North Sterling Reservoir was 161 μg/L and the mean concentration at Prewitt Reservoir was 100 μg/L greater. Although this is a large difference in concentrations, both are classified as eutrophic, not reflecting the higher phosphorous concentration at Prewitt Reservoir. The indices are use only for minimal description of the reservoirs.

Similar to the EPA method at Jackson Reservoir, TP concentrations result in higher trophic classification by the Carlson method than does chlorophyll-*a*. Carlson index values for lakes in Poland also yielded the highest classification based upon TP concentrations (Hillbricht-Ilkowska and Wisniewski 1993). One strength of the Carlson method is that it allows a gradient of numerical classifications so that information is retained, unlike the fixed boundary systems. The reservoirs are classified between approximately 0 and 100, with occasional classification greater than 100. Using this system it is possible to decide which parameter, chlorophyll-*a*, TP or Secchi disk depth, would be most appropriate for the system. For example, in the South Platte off channel storage reservoirs with high TP concentrations and high turbidity, primary production may be a better metric upon which to base trophic status indices.

Although the Carlson TSI offers the advantage of retaining information about the system, there are several reasons why it may not be appropriate for the reservoirs. First, this study has shown the importance of total and inorganic-N in contributing to primary production in South Platte Basin Reservoirs. Based upon linear regression with *log* TP alone, only 50 percent of the chlorophyll-*a* was described, but this value increased to between 60 and 80 percent by including nitrogen. The abilities of the Carlson TSI to describe the system are limited since it does not include nitrogen. The TP and chlorophyll-*a* equation was evaluated along with 23 other equations utilized in the model worksheet (Appendix D); it gave the smallest percentage error at Jackson Reservoir, but other equations provided a better determination of chlorophyll-*a* based upon phosphorous concentrations. Also, the use of Secchi depth in the reservoirs may not yield accurate values, depending upon the non-chlorophyll light attenuating substance in the water. Carlson advised that chlorophyll-*a* be used instead of Secchi depth whenever possible (Carlson, 1980).

The Carlson Index was used to evaluate the trophic state of Arvada Reservoir using all three indicator variables (USGS 1987). The TSI values based upon Secchi disk depth and chlorophyll were similar, but TP index values were less. In contrast, TP index values were often greater than chlorophyll-a or Secchi depth values on off-channel storage reservoirs. Arvada Reservoir would be classified as oligotrophic based upon TP and mesotrophic based upon Secchi depth and chlorophyll-*a* concentration. In contrast, off-channel storage reservoirs were typically eutrophic.

The high nutrient concentrations and loads coming into the reservoirs result in a eutrophic classification using the Vollenweider plot. This plot is useful in that the proximity of the trophic state of the lake or reservoir can be seen in relation to the others plotted on the graph. In addition, Vollenweider developed a plot based upon incoming TP concentration rather than loads (Vollenweider 1976), which may be useful where annual loading information is not available.

The OECD probability plots, also developed by Vollenweider and others, are useful in that they recognize the uncertainty of the trophic designations and report the trophic state as a probability. However, these plots rely upon the average chlorophyll-*a* and TP concentrations. These measurements are not normally distributed and it may improve the plots to use the median value. In addition, these measures say nothing about the phosphorous, chlorophyll-*a* or transparency relationships within the reservoir.

Analysis of the TP models that predict chlorophyll-*a* was completed using several metrics (r^2 of log and untransformed values, 95% confidence interval for the calculated chlorophyll, percentage error and actual error). Different equations were best depending upon which metric was evaluated, but for Sterling and Prewitt Reservoirs, one model had the best fit with several different measurements. The North Sterling Reservoir correlation coefficient, percent error and average error were all best using the multivariate relationship. As a result, an equation using nitrogen and phosphorous is recommended for North Sterling Reservoir predictions (Smith 1982). The lowest average error at Jackson Reservoir was derived from a nitrogen based equation (Brezonik 1984), but the correlation coefficient, confidence interval and percent error are best using TP alone. The equation with the highest *log* and untransformed correlation coefficients and the smallest confidence interval was developed for Florida Lakes (Baker et al. 1981). At Prewitt Reservoir, the equation with the lowest average and percentage error and the typical correlation coefficient (r=.52) was developed in 2000 using annual mean phosphorous and chlorophyll data for 274 lakes (Brown et al. 2000). Equations were also developed for nitrogen alone and nitrogen and phosphorous, but the TP equation gave the lowest values. Thus, different equations were determined at each reservoir to best represent the nutrient~chlorophyll-*a* relationship.

CONCLUSIONS

The objectives of this study were to determine the concentrations, changes over time and relationships between phosphorous, nitrogen and chlorophyll-*a* in off channel storage reservoirs along the South Platte River. The median TP concentration was greatest at Prewitt Reservoir (267 μg/L), followed by Sterling (183 μg/L) and Jackson (91 μg/L). The Chlorophyll-*a* median concentration was greatest at Prewitt (142 μg/L), then Sterling (46 μg/L) and Jackson (45 μg/L). This study found a positive correlation between TP and chlorophyll-*a* at North Sterling (*log* chl-*a* =0.78(*log* TP) + 0.04) and Jackson Reservoir (*log* chl-*a*=1.70(*log* TP) – 2.27)), but no significant correlation (α=0.10) at Prewitt Reservoir. A negative correlation between inorganic-N and chlorophyll-*a* was observed at Sterling Reservoir (*log* chl-*a* = 3.25 – 0.489 (*log* inorganic-N)). The use of nitrogen or inorganic nitrogen along with TP improved the ability to predict chlorophyll-*a*. The use of TP and TN made the relationship at Prewitt Reservoir, which was not significant based upon TP alone, significant at α=0.10 (r^2=0.61; p=0.10; n=8) (*log* chl-*a* = 2.80 + 3.88 (*log* TP) – 2.92 (*log* TN)). The use of TN with TP strengthened the TP equation, resulting in the equation with the greatest correlation coefficient at Jackson Reservoir (r^2=0.67) (*log* chl-*a*=1.84 + 3.55 (*log* TP) – 2.47 (*log* TN)), while inorganic-N gave the strongest equation at North Sterling Reservoir (r^2=0.83) (*log* chl-*a* = 2.24 + 0.32 (*log* TP) – 0.39 (*log* inorganic-N)). Prewitt Reservoir was different from the other reservoirs with no significant relationship between TP and chlorophyll-*a* and no seasonal nitrate decline.

The TP concentrations of greater than 100 μg/L, as well as the seasonal nitrate declines, result in potential co-limitation of primary production, wherein both nitrogen and phosphorus limit growth part of the time in Jackson and Prewitt Reservoirs.

The implications of these nutrient relationships on TSI models and alga growth were examined. Traditional TSI applicability in the South Platte Basin off channel storage reservoirs is hindered because nitrogen is not included in the typical equations. In addition, high TP concentrations often yield a higher trophic state than an index reflecting the response of the system (chlorophyll-*a*). The seasonal nutrient decline affects the traditional TP~chlorophyll-*a* model as nitrogen may limit production.

North Sterling Reservoir is phosphorous limited based upon bioavailable nutrient concentrations, however seasonal TN:TP ratios decline into co-limiting classifications. In addition, the highest correlation coefficient (r=0.91; p=0.01) occurred when considering TP and inorganic-N (*log* chl-*a* = 2.24 + 0.32 (*log* TP) – 0.39 (*log* inorganic-N). When evaluating other models the TN and TP models worked best based upon correlation coefficient, average error and percent error. Although the reservoir is classified as eutrophic to hypereutrophic, classification based upon TP was greater than chlorophyll-*a* for Carlson's TSI and OECD probability. The factors combined suggest that trophic state assessment of Sterling should be done using both phosphorous and nitrogen.

Prewitt Reservoir differed from Sterling and Jackson in that there was no relation (at α=0.10) between TP and chlorophyll-*a* and no decline in nitrate over time. The only significant regression was multiple regression using both TP and TN to predict chlorophyll-*a* (r=0.78; p=0.10; n=8). It was the most eutrophic reservoir based upon indices, and median phosphorous and chlorophyll-*a* concentrations. Model selection methods indicate that TP and TN should be used in predicting primary production. However, current TN and TP models did not predict chlorophyll-*a* well (based upon correlation coefficients) and the data collected in this study may serve as a better basis for a nutrient~chlorophyll-*a* model at Prewitt Reservoir.

Jackson is potentially co-limited based upon nutrient concentrations and exhibits nitrate and nutrient ratio declines over the study period. Given that Jackson Reservoir is potentially co-limited, that nutrient ratios decline and that the best average error was determined using TN, TN and TP should be used when assessing Jackson Reservoir trophic status.

This study found the linear relationship between TP and chlorophyll-*a* to be strengthened by the inclusion of TN in multivariate analysis. Nutrient concentrations, ratios and declines indicate that nitrogen and phosphorous should be considered at all three reservoirs when evaluating reservoir eutrophication. This study found that in these hypereutrophic reservoirs, production should be evaluated with the recognition that nitrogen may be limiting and nutrient criteria should be determined with consideration of the present nutrient and chlorophyll concentrations.

RECOMMENDATIONS

Since concentrations of nitrogen and phosphorous can increase even when filling is not occurring, other sources of nutrient inputs should be evaluated. One source of phosphorous may be release from the sediments during anoxic conditions in the hypolimnion. Thus, aeration or minimization of the cause of these conditions may decrease the phosphorous availability and concentrations. Erosion is another source of phosphorous addition to the aquatic ecosystem, therefore any erosion control that could be implemented along the inlet canals and from the banks of the reservoirs would be beneficial.

Nitrate concentrations decline in the reservoirs. This finding supports the use of the reservoirs as a passive nitrate mitigation strategy from the basin. However, since phosphorous does not have a mechanism for removal as nitrate does (denitrification), it is possible that phosphorous concentrations will continue to increase in the reservoirs. Flows with water lower in phosphorous concentrations may serve to remove some of the accumulated phosphorous concentrations.

The finding that an *Anabena* bloom occurred at Sterling Reservoir when PO_4^{3-} concentrations were below the typical limiting concentration (3 μg/L) indicates that the bloom was most likely limited by ambient PO_4^{3-} concentrations. Measures to decrease phosphorous may be important to future management. However, a model using both nitrogen and phosphorous resulted in the strongest correlation coefficient, average error and percent error at North Sterling Reservoir during precision analysis and should be employed in future management decision making. A continued occurrence of toxic blue-green algae was found following nutrient reduction and fish biomanipulation rehabilitation practices (Cronberg et al. 1999), so nutrient reduction alone may not mitigate future problems.

Nutrient concentrations and the trophic state of the reservoirs should be monitored. A trophic state index that accounts for the nitrate trend and the relationship between phosphorous and nitrogen with primary production, as measured by chlorophyll-*a*, should be used. Chlorophyll-*a*, the response variable, should be measured when determining the trophic state. Nitrogen and phosphorous concentrations should also be measured and used in trophic state determination since primary production in all reservoirs was best determined using TP and TN.

The primary use is irrigation and the secondary use is contact recreation. However, given the high nutrient concentrations and previously observed cyanobacterial blooms, it is likely that more blooms will occur in the future that may interfere with recreation. If blooms do occur, it is not recommended to use any agent to control the blooms as this will cause cell lysis and may increase cyanobacterial toxin input into the water. Cyanobacterial toxins have been shown to cause fish death and be skin irritants. In addition, microcystin is a hepatotoxin and has been implicated in liver cancer and resulted in human death at a dialysis clinic in Brazil (Van Dolah 2000). If cyanobacterial blooms occur at the reservoir, access should be restricted to Class 2 recreation rather than primary contact recreation. Additionally, if reservoir water is used to provide drinking water, it should be tested and treated to remove any hepatotoxins within the water. Until further research is conducted on these toxins, the potential of human contact should be minimized.

Management alternatives often focus on nutrient reduction to control algae growth, but since internal loading may be the source on phosphorous in the reservoirs, a plan similar to one developed for Lake Apopka, Florida may be appropriate (Canfield et al. 2000). The plan to build artificial reefs to support a largemouth bass fishery stems from the acknowledgement that not all lakes are nutrient limited. Contrary to convention, nutrient control strategies are not the only option for lake restoration. In fact, a three-fold plan to rehabilitate a hypereutrophic reservoir was designed to: 1) reduce external phosphorous loading, 2) reduce internal phosphorous loading and 3) reduce trophic status through biomanipulation. Biomanipulation was the most successful of the three options at reducing the trophic state of the reservoir (Robertson et al. 2000).

Future studies should include the use of mesocosms to study the nutrient limiting algae growth though the addition of nutrients and observing the responses. A more detailed compilation of the algae present at the reservoir, along with the counts to determine the dominant species and population shifts over the season along with low level nutrient analysis would greatly increase our knowledge of the reservoirs. Sediment core samples and depth integrated chlorophyll-a samples using a tube through the photic zone may be helpful in future studies. A study on the sources of the nutrients, especially the increase in phosphorous without reservoir inflows, within each reservoir would aid in problem mitigation and management.

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APPENDICES

Appendix A: Reservoir Volume, Inflow and Outflow

Appendix B: Data elements for reporting water quality results

Appendix C: Data

C-1 Physical Parameters

C-2 Secchi Depth

C-3 CSU Soil, Water and Plant testing lab data set

C-4 Chlorophyll results

Appendix D: Total nutrient ~ chlorophyll-a models evaluated in the TSI worksheet

Appendix A Reservoir Volume, inflow and outflow

North Sterling Reservoir, 2001

Month	Storage First day of month in acre-feet (ha-m)	Monthly inflow in acre-feet (ha-m)	Mean monthly inflow in acre-feet/ (ha-m/day)	Monthly outflow in acre-feet (ha-m)	Mean monthly outflow in acre-feet/day (ha-m/day)
January	37,300 (4,601)	14,980 (1,848)	483 (60)	0	0
February	48,450 (5,976)	13,590 (1,676)	485 (60)	0	0
March	59,470 (7,336)	17,827 (2,199)	660 (81)	0	0
April	74,800 (9,236)	3,789 (467)	126 (16)	1,258 (155)	105 (13)
May	75,020 (9,254)	20,307 (2,505)	655 (81)	14,060 (1,734)	454 (56)
June	74,590 (9,201)	10,420 (1,285)	521 (64)	16,960 (2,092)	565 (70)
July	63,610 (7,846)	0	0	22,390 (2,762)	722 (89)
August	41,240 (5,087)	0	0	23,740 (2,928)	766 (94)
September	17,700 (2,183)	656 (81)	66 (8)	8,340 (1,029)	397 (49)
October	9,510 (1,173)	11,676 (1,440)	377 (46)	2,100 (259)	263 (32)
November	13,980 (1,724)	16,600 (2,048)	755 (93)	0	0

Prewitt Reservoir, 2001

Month	Storage First day of month in acre-feet (ha-m)	Monthly inflow in acre-feet (ha-m)	Mean monthly inflow in acre-feet/day (ha-m/day)	Monthly outflow in acre-feet (ha-m)	Mean monthly outflow in acre-feet/day (ha-m/day)
January	21,790 (2,688)	8,070 (995)	260 (32)	0	0
February	26,320 (3,247)	2,620 (323)	94 (12)	0	0
March	26,540 (3,274)	4,650 (574)	150 (19)	0	0
April	28,600 (3,528)	2,070 (255)	69 (9)	275 (34)	46 (6)
May	28,600 (3,528)	1,590 (196)	59 (7)	0	0
June	28,020 (3,456)	2,070 (255)	104 (13)	1,947 (240)	195 (24)
July	25,200 (3,108)	930 (115)	310 (38)	4,048 (499)	169 (21)
August	20,070 (2,476)	0	0	4,158 (513)	134 (17)
September	14,850 (1,832)	0	0	1,468 (181)	113 (14)
October	12,730 (1,570)	0	0	0	0
November	12,120 (1,495)	0	0	0	0

Jackson Reservoir, 2001

Month	Storage First day of month in acre-feet (ha-m)	Monthly inflow in acre-feet (ha-m)	Mean monthly inflow in acre-feet/day (ha-m/day)	Monthly outflow in acre-feet (ha-m)	Mean monthly outflow in acre-feet/day (ha-m/day)
January	20,900 (2,577)	0	0	0	0
February	22,161 (2,733)	3,869 (477)	242 (30)	0	0
March	25,320 (3,123)	4,740 (585)	222 (27)	0	0
April	27,256 (3,362)	1,540 (190)	104 (13)	0	0
May	25,751 (3,176)	550 (68)	101 (12)	0	0
June	27,256 (3,362)	0	0	2,404 (297)	400 (49)
July	21,530 (2,655)	0	0	9,837 (1213)	428 (53)
August	15,585 (1,922)	0	0	15,257 (1881)	508 (63)
September	5,064 (625)	0	0	44 (5)	44 (5)
October	0	0	0	0	0
November	0	0	0	0	0

Appendix B Data elements for reporting water quality results

Contact: *Dr. John Stednick, Colorado State University, 322 Natural Resources Building, Ft. Collins, Colorado 80523-1482; (970) 491-7248; jds@cnr.colostate.edu*

Sampling Person: Emile B. Hall, Same address as above; (970) 282-7718; emile@lamar.colostate.edu

Laboratory Name and Address - Nutrient data:

Colorado State University, Soil, Water and Plant Testing Laboratory
Natural and Environmental Sciences Building - A319, Ft. Collins, Colorado 80523
(970) 491-5061; jself@ceres.agsci.colostate.edu

Laboratory Name and Address - Chlorophyll-*a* data

Bureau of Reclamation, Chris Holdren, 6th and Kipling
Building 67, Room 152, Denver, Colorado 80225
(303) 445-2178; choldren@do.usbr.gov

Results: *Appendix C*

Location:

Sampling coordinates:

Reservoir	Site number	Altitude	Coordinates
North Sterling Reservoir	Site 1:	4,096 ft	N 40° 46' 70" W 103° 16' 27"
	Site 2:		N 40° 47' 15" W 103° 16' 57"
	Site 3:		N 40° 46' 16" W 103° 18' 01"
Prewitt Reservoir	Site 4: Boat Dock	4,127 ft	N 40° 25' 12" W 103° 22' 78"
Jackson Reservoir	Site 5:	4,461 ft	N 40° 23' 37" W 104° 05' 37"
	Site 6:		N 40° 22' 71" W 104° 04' 58"
	Site 7		N 40° 23' 53" W 104° 03' 42"
	Site 8: off shore measurement		Not available

Latitude/Longitude Accuracy: 1-5 meters
Latitude/Longitude Method: Garmin GPS 12-Personal Navigator

Nutrient sample collection sites per day:

Reservoir	4/10	5/12	6/7	6/21	7/5	7/19	8/2	8/25	9/22	10/8
N. Sterling	Dock	2	1	1	1	1	1	1	1	1
Prewitt	4	4	4	4	4	4	4	4	4	4
Jackson	Dock	5	5	5	5	5	5	Shore	Shore	Shore

Bottom Depth Measure (in meters):

	North Sterling Reservoir			Jackson Reservoir		
Date	Site 1	Site 2	Site 3	Site 5	Site 6	Site 7
4/10/01	--	--	--	--	--	--
5/12/01	11.2	8.0	8.5	5.0	3.5	3.4
6/7/01	10.7	11.3	6	5.0	3.8	3.6
6/21/01	8.2	11.5	4.1	2.9	3.7	3.0
7/5/01	11.4	11.3	8	1.4	3.0	2.3
7/19/01	13	10	5.3	3.6	2.8	2.6
8/2/01	9	6.8	4.8	2.2	2.1	1.3
8/25	8.3	5.6	3.0	--	--	--
9/22	3.3	1.6	0.9	--	--	--
10/8	--	--	--	--	--	--

-- indicates that measurements were taken only at the reservoir surface

Sample Collection Water Depth **-** Appendix C.1, C.2 or Table 9
Sample Temperature - Appendix C.1; Sample Identification – Appendix C
Sample Collection Method - Surface Water Grab Samples

Sample Preservation / Treatment
Container Type - HDPE; Container Color - Opaque; Container size - 1 liter
Sample collection filtering - unfiltered; Chemical preservation method - none
Temperature preservation method - Cold Packs and Refrigeration

Sample Analysis (Appendix C.2)
Analytical Method:

Constituent	CSU Method	Detection Limit	NAWQA Method
Ammonia Nitrogen 4500-NH_3	Automated Pheante EPA 350.1	0.1 mg/L	Titrimetric Method
Nitrite	Ion Chromatographic SM 4500-NO_2 -	0.1 mg/L	Low Range Cadmium Reduction Hach Method 8192
Nitrate	Cadmium reduction SM 4500-NO_3- E	0.1 mg/L	
Ammonia and Organic Nitrogen	Semi-Micro Kjeldahl SM 4500-N_{org}	0.1 mg/L	Macro-Kjeldahl
Total Phosphorous	Digest Ion Chromatography SM 4110 B	0.001 mg/L	Ascorbic acid
Orthophosphorous	Ascorbic acid SM 4500-P	0.001 mg/L	Ascorbic acid
Chlorophyll-a	Spectrophotometric determination SM 10200 H	--	High performance liquid chromatography

Constituents analyzed per sampling date:

Constituent	4/10	5/12	6/7	6/21	7/5	7/19	8/2	8/25	9/22	10/8
Ammonia	X	X	X	X	X	X	X	X	X	X
Organic Nitrogen	X	X	X	X	X	X	X	X	X	X
Nitrate	X	X	X	X	X	X	X	X	X	X
Nitrite			X	X		X			X	X
Total Phosphorous	X	X	X	X	X	X	X	X	X	X
Ortho phosphorous		X	X	X	X	X	X	X	X	X

Appendix C.1 Physical Parameters

Removed data points are in **Bold**

	Site No	Date	Time	Temp	Spec. Cond.	Dissolved Oxygen	Dissolved Oxygen	Depth	pH	ORP
			hh:mm	°C	μS/cm	%	mg/L	meters		mV
North Sterling Reservoir	dock	4/10/01	11:16	8.2	1592	91.3	10.72	0.1	8.7	279
	1	5/12/01	10:17	14.4	1530	139.9	14.23	1.2	8.6	189.3
	1	5/12/01	10:19	14.3	1531	136.3	13.91	5.5	8.6	208.6
	1	5/12/01	10:22	10.5	1593	63.1	7.01	11.2	8.4	217.4
	2	5/12/01	10:35	14.8	1515	156.3	15.75	1.0	8.7	210.5
	2	5/12/01	10:40	13.7	1537	123.2	12.71	5.1	8.5	224.7
	2	5/12/01	10:48	11.5	1583	83.2	9.02	7.6	8.5	155.7
	3	5/12/01	11:20	15.7	1515	181.5	17.97	1.3	8.7	175.5
	3	5/12/01	11:23	11.5	1578	83	9.01	4.5	8.5	192.8
	3	5/12/01	11:26	10.4	1595	48.5	5.40	8.5	8.3	199.3
	1	6/7/01	9:39	15.3	1510	41.9	4.18	10.7	7.8	186
	1	6/7/01	9:40	15.6	1502	37.2	3.69	9.7	7.9	189
	1	6/7/01	9:40	15.8	1496	44.5	4.39	8.5	7.9	192
	1	6/7/01	9:40	15.9	1495	47.5	4.69	7.5	7.9	194
	1	6/7/01	9:41	15.9	1494	49	4.82	6.4	8.0	195
	1	6/7/01	9:41	16.0	1491	50.7	4.99	5.4	8.0	197
	1	6/7/01	9:41	16.0	1490	52.2	5.13	4.0	8.0	199
	1	6/7/01	9:42	16.1	1489	53.4	5.23	3.0	8.0	200
	1	6/7/01	9:42	16.2	1488	55.3	5.42	2.0	8.0	201
	1	6/7/01	9:42	16.2	1489	57	5.58	0.9	8.1	202
	2	6/7/01	10:00	15.5	1506	48.5	4.82	11.3	8.0	244
	2	6/7/01	10:00	15.3	1511	35.3	3.53	9.7	7.9	229
	2	6/7/01	10:01	15.4	1508	**148.6 a**	**14.78 a**	7.3	7.9	230
	2	6/7/01	10:02	15.6	1508	37.5	3.71	6.7	7.9	232
	2	6/7/01	10:02	16.0	1504	43.3	4.25	5.4	8.0	230
	2	6/7/01	10:03	16.6	1497	55.8	5.41	3.8	8.1	229
	2	6/7/01	10:03	17.4	1490	75.7	7.22	2.1	8.3	227
	2	6/7/01	10:04	17.6	1488	83.1	7.90	1.0	8.3	228
	2	6/7/01	10:04	17.6	1488	84.8	8.06	0.6	8.4	228
	3	6/7/01	10:17	17.8	1491	78.3	7.41	0.2	8.2	244
	3	6/7/01	10:18	18.2	1479	90.6	8.50	0.9	8.4	228
	3	6/7/01	10:18	17.9	1481	88.4	8.34	2.0	8.4	229
	3	6/7/01	10:20	17.7	1481	84	7.96	3.7	8.4	233
	3	6/7/01	10:21	17.6	1483	81	7.70	5.0	8.4	234
	3	6/7/01	10:21	17.6	1482	79.4	7.54	5.8	8.4	236
	3	6/7/01	10:22	17.6	1485	79.1	7.52	6.0	8.4	236
	1	6/21/01	9:40	18.8	1492	87.9	8.16	0.8	8.2	224.8

North Sterling Reservoir	1	6/21/01	9:41	18.6	1492	88.9	8.28	1.3	8.2	229.3
	1	6/21/01	9:42	18.5	1493	76.6	7.15	2.4	8.2	232.8
	1	6/21/01	9:43	18.5	1493	73.5	6.85	3.4	8.2	236.3
	1	6/21/01	9:44	18.5	1493	73.5	6.86	4.2	8.2	236.9
	1	6/21/01	9:44	18.5	1492	74.4	6.94	4.8	8.3	238.7
	1	6/21/01	9:45	18.5	1492	74.1	6.91	5.5	8.3	239.6
	1	6/21/01	9:46	18.5	1492	72.2	6.75	6.5	8.3	241.3
	1	6/21/01	9:47	18.4	1493	70.3	6.57	7.2	8.3	242.6
	1	6/21/01	9:48	18.4	1494	69.5	6.49	8.2	8.2	243.7
	2	6/21/01	10:26	18.5	1510	103.1	9.62	0.7	8.4	214.2
	2	6/21/01	10:28	18.9	1492	102	9.44	1.6	8.5	216.7
	2	6/21/01	10:28	18.6	1494	82.6	7.68	2.6	8.4	221.6
	2	6/21/01	10:29	18.5	1494	71.7	6.69	3.6	8.3	224.9
	2	6/21/01	10:30	18.5	1494	72.9	6.81	4.6	8.3	226.6
	2	6/21/01	10:31	18.4	1496	65.3	6.11	5.6	8.3	230.6
	2	6/21/01	10:32	18.3	1499	47.7	4.47	6.6	8.2	234.5
	2	6/21/01	10:33	18.1	1502	27.7	2.61	7.6	8.1	238.8
	2	6/21/01	10:34	17.9	1506	13.3	1.25	8.6	8.0	242.4
	2	6/21/01	10:34	17.7	1508	**-1.6 b**	**-0.15 b**	9.5	7.9	244.4
	2	6/21/01	10:36	17.6	1510	**-12.4 b**	**-1.17 b**	10.5	7.8	246
	2	6/21/01	10:37	17.6	1510	**-16.5 b**	**-1.57 b**	11.5	7.8	246.2
	3	6/21/01	10:58	19.6	1479	118	10.78	0.4	8.3	218.9
	3	6/21/01	10:58	19.4	1475	163.5	14.99	1.3	8.5	203.7
	3	6/21/01	10:59	19.2	1477	149.3	13.73	2.3	8.5	209.3
	3	6/21/01	10:59	19.1	1477	139	12.80	3.5	8.4	211.9
	3	6/21/01	11:00	19.1	1478	131.9	12.15	4.1	8.4	214.3
	1	7/5/01	9:25	22.7	1479	**69.7 c**	**5.99 c**	0.3	7.9	183
	1	7/5/01	9:25	22.7	1479	74.2	6.37	0.3	7.9	188
	1	7/5/01	9:26	22.7	1479	74.2	6.37	0.7	7.9	193
	1	7/5/01	9:26	22.6	1479	71.7	6.17	1.6	7.9	199
	1	7/5/01	9:27	22.5	1479	67.5	5.81	2.1	7.9	204
	1	7/5/01	9:28	22.4	1479	64.5	5.58	2.7	7.9	210
	1	7/5/01	9:29	22.2	1481	57.9	5.03	3.5	7.8	216
	1	7/5/01	9:29	22.1	1482	56.1	4.87	4.0	7.8	218
	1	7/5/01	9:30	22.0	1482	51	4.44	5.2	7.7	223
	1	7/5/01	9:30	21.9	1482	47.5	4.14	5.4	7.7	225
	1	7/5/01	9:31	21.7	1483	36.9	3.23	5.8	7.6	229
	1	7/5/01	9:32	21.5	1484	29	2.55	6.5	7.6	233
	1	7/5/01	9:33	21.3	1485	25.1	2.21	7.3	7.5	235
	1	7/5/01	9:33	20.3	1487	9.5	0.85	9.5	7.5	239
	1	7/5/01	9:34	19.4	1487	1.6	0.15	11.4	7.4	234
	2	7/5/01	9:43	**22.3 c**	1508	**87.3 c**	**7.56 c**	0.1	**7.8 c**	236
	2	7/5/01	9:43	23.3	1479	86.4	7.33	0.2	8.1	214
	2	7/5/01	9:44	23.3	1477	86.6	7.35	1.1	8.1	216
	2	7/5/01	9:44	23.3	1478	85.7	7.28	1.4	8.1	217

North Sterling Reservoir	2	7/5/01	9:45	23.3	1478	83	7.05	2.4	8.1	220
	2	7/5/01	9:46	22.6	1481	64.1	5.52	3.4	7.9	228
	2	7/5/01	9:47	22.2	1484	52.9	4.59	4.4	7.9	231
	2	7/5/01	9:47	21.6	1483	41.2	3.62	5.1	7.7	237
	2	7/5/01	9:48	21.5	1485	32.2	2.83	5.7	7.7	240
	2	7/5/01	9:49	21.4	1486	27.8	2.45	6.7	7.6	242
	2	7/5/01	9:49	21.1	1487	21.1	1.87	7.8	7.5	244
	2	7/5/01	9:50	20.6	1488	14.2	1.27	8.8	7.5	246
	2	7/5/01	9:50	19.8	1493	3.8	0.35	10.6	7.5	248
	2	7/5/01	9:51	19.5	1495	0.3	0.02	11.3	7.4	200
	3	7/5/01	10:04	23.4	1469	69.6	**5.90 c**	0.7	8.2	189
	3	7/5/01	10:05	23.4	1468	96.3	8.16	0.7	8.2	193
	3	7/5/01	10:05	23.3	1469	96.4	8.18	2.3	8.2	198
	3	7/5/01	10:06	23.3	1469	95.4	8.10	3.2	8.2	200
	3	7/5/01	10:06	23.3	1469	91.1	7.75	4.1	8.2	204
	3	7/5/01	10:07	22.2	1478	52.5	4.55	5.6	7.9	216
	3	7/5/01	10:07	21.7	1481	41.6	3.64	6.4	7.8	220
	3	7/5/01	10:08	21.2	1483	28.8	2.54	7.6	7.7	223
	3	7/5/01	10:08	21.1	1484	23	2.04	8.0	7.6	204
	1	7/19/01	9:21	25.4	1418	130.2	10.64	0.4	8.1	211
	1	7/19/01	9:22	25.0	1421	117.7	9.68	1.0	8.2	224
	1	7/19/01	9:23	24.8	1423	100.1	8.27	1.6	8.1	230
	1	7/19/01	9:23	24.6	1427	82.5	6.84	2.6	8.1	234
	1	7/19/01	9:23	24.5	1428	74.9	6.22	3.2	8.1	237
	1	7/19/01	9:24	24.3	1432	54.9	4.58	3.8	7.9	245
	1	7/19/01	9:25	24.2	1433	35.4	2.96	4.4	7.8	251
	1	7/19/01	9:25	24.2	1432	29.3	2.45	4.8	7.8	254
	1	7/19/01	9:26	24.1	1432	28.1	2.35	5.6	7.7	255
	1	7/19/01	9:26	24.1	1432	26.8	2.24	6.3	7.7	257
	1	7/19/01	9:27	24.0	1433	23.8	2.00	7.3	7.7	259
	1	7/19/01	9:27	24.0	1434	22.8	1.91	8.0	7.6	259
	1	7/19/01	9:28	23.9	1434	20.7	1.74	8.7	7.6	261
	1	7/19/01	9:29	23.8	1437	17.5	1.48	9.3	7.6	262
	1	7/19/01	9:29	23.4	1440	12.6	1.07	9.9	7.6	262
	1	7/19/01	9:29	22.6	1446	6.8	0.58	10.6	7.5	258
	1	7/19/01	9:30	21.4	1453	5.7	0.50	11.6	7.5	247
	1	7/19/01	9:31	20.4	1457	5.5	0.50	12.5	7.5	235
	1	7/19/01	9:31	19.7	1466	5.2	0.47	13.0	7.4	177
	2	7/19/01	9:50	26.0	1412	138.2	11.17	0.3	8.5	172
	2	7/19/01	9:51	25.4	1414	113.2	9.25	1.3	8.4	191
	2	7/19/01	9:51	24.7	1426	60.8	5.03	3.0	8.1	205
	2	7/19/01	9:52	24.4	1431	34.5	2.87	3.8	8.0	210
	2	7/19/01	9:52	24.2	1435	23.2	1.94	4.8	7.9	213
	2	7/19/01	9:53	24.1	1436	20.2	1.69	4.9	7.8	214
	2	7/19/01	9:53	24.0	1436	19.6	1.64	6.0	7.8	215

North Sterling Reservoir	2	7/19/01	9:53	24.0	1437	18.1	1.52	6.2	7.8	216
	2	7/19/01	9:54	23.9	1438	17.7	1.49	6.8	7.8	216
	2	7/19/01	9:54	23.8	1439	14.6	1.23	8.0	7.7	217
	2	7/19/01	9:55	23.1	1440	9.6	0.82	9.9	7.7	209
	2	7/19/01	9:55	22.9	1443	7.7	0.66	10.0	7.6	182
	3	7/19/01	10:08	25.5	1416	163.4	**13.34 c**	0.5	8.5	158
	3	7/19/01	10:08	25.5	1416	150	12.23	0.6	8.6	165
	3	7/19/01	10:08	25.4	1417	142.7	11.67	1.3	8.6	178
	3	7/19/01	10:09	25.1	1423	110	9.05	2.4	8.4	189
	3	7/19/01	10:09	24.5	1431	46.4	3.85	3.5	8.1	204
	3	7/19/01	10:10	24.3	1432	39.7	3.31	4.3	8.0	207
	3	7/19/01	10:10	24.2	1433	27.3	2.28	5.4	7.9	209
	3	7/19/01	10:11	24.2	1433	22.3	1.86	5.4	7.8	205
	3	7/19/01	10:11	24.2	1433	20.4	1.70	5.3	7.8	201
	1	8/2/01	9:26	24.9	1434	5.2	**0.43 d**	0.4	7.6	200
	1	8/2/01	9:26	24.7	1431	61.6	5.10	1.3	7.7	210
	1	8/2/01	9:27	24.6	1431	55.8	4.63	2.3	7.7	216
	1	8/2/01	9:27	24.5	1430	50.6	4.20	3.4	7.7	221
	1	8/2/01	9:28	24.5	1431	49.1	4.08	4.0	7.7	223
	1	8/2/01	9:29	24.4	1432	44.7	3.72	5.9	7.7	228
	1	8/2/01	9:29	24.4	1432	43.7	3.64	6.6	7.7	230
	1	8/2/01	9:30	24.4	1432	42.2	3.51	7.5	7.7	233
	1	8/2/01	9:30	24.4	1432	39.4	3.28	9.0	7.7	235
	2	8/2/01	9:49	25.2	1425	53.8	**4.41 c**	0.4	8.2	205
	2	8/2/01	9:49	25.3	1427	88.3	7.23	0.4	8.2	205
	2	8/2/01	9:49	25.1	1426	85.7	7.04	1.3	8.2	210
	2	8/2/01	9:50	24.8	1429	64.4	5.32	2.1	8.1	216
	2	8/2/01	9:50	24.8	1430	57.1	4.72	2.6	8.1	220
	2	8/2/01	9:51	24.7	1431	52.5	4.35	3.5	8.0	224
	2	8/2/01	9:51	24.6	1431	46.5	3.86	4.5	7.9	228
	2	8/2/01	9:52	24.5	1432	40.8	3.39	5.6	7.9	230
	2	8/2/01	9:53	24.4	1435	26	2.16	6.6	7.8	232
	2	8/2/01	9:53	24.5	1434	25.7	2.13	6.8	7.8	228
	2	8/2/01	9:54	24.5	1434	151	**12.54 d**	6.8	7.8	222
	3	8/2/01	10:06	24.8	1435	82.5	6.82	0.2	8.1	204
	3	8/2/01	10:06	25.2	1422	81.4	6.68	1.0	8.2	203
	3	8/2/01	10:07	25.1	1420	76.7	6.30	1.7	8.2	207
	3	8/2/01	10:07	25.0	1420	66.7	5.49	2.5	8.2	210
	3	8/2/01	10:07	24.9	1417	65.2	5.38	4.6	8.2	212
	3	8/2/01	10:08	24.8	1421	59.7	4.93	4.8	8.1	215
	1	8/25/01	9:46	22.2	1440	89.4	7.76	0.7	7.6	218
	1	8/25/01	9:46	22.2	1439	58.9	5.10	1.0	7.6	223
	1	8/25/01	9:47	22.2	1440	56.3	4.89	1.4	7.6	225
	1	8/25/01	9:47	22.2	1439	51.7	4.49	2.0	7.6	229

North Sterling Reservoir	1	8/25/01	9:47	22.1	1438	46.7	4.06	2.4	7.6	232
	1	8/25/01	9:48	22.1	1438	43.3	3.77	2.7	7.6	233
	1	8/25/01	9:48	22.1	1439	42.8	3.72	3.0	7.6	234
	1	8/25/01	9:48	22.1	1441	41	3.56	3.5	7.6	236
	1	8/25/01	9:49	22.1	1440	39.6	3.44	3.9	7.6	237
	1	8/25/01	9:49	22.1	1440	37.9	3.29	5.5	7.6	238
	1	8/25/01	9:49	22.1	1439	36	3.13	7.1	7.6	239
	1	8/25/01	9:50	22.0	1442	33.2	2.89	8.4	7.6	239
	1	8/25/01	9:50	**22.0 c**	1443	28.8	2.51	8.3	7.6	229
	2	8/25/01	10:03	22.9	1419	89.9	7.69	0.3	8.1	220
	2	8/25/01	10:04	23.0	1420	97.4	8.32	1.0	8.4	221
	2	8/25/01	10:04	22.9	1422	94	8.04	1.6	8.3	224
	2	8/25/01	10:04	22.8	1424	88.6	7.61	2.2	8.2	229
	2	8/25/01	10:05	22.4	1430	62.7	5.42	2.9	8.1	237
	2	8/25/01	10:05	22.2	1431	54.5	4.73	3.7	8.0	241
	2	8/25/01	10:05	22.1	1433	38.6	3.36	4.7	7.9	245
	2	8/25/01	10:06	22.0	1434	28.1	2.45	5.4	7.8	246
	2	8/25/01	10:06	22.0	1435	24.1	2.10	5.6	7.8	245
	3	8/25/01	10:20	23.2	1430	79	6.72	0.7	8.3	209
	3	8/25/01	10:20	23.2	1430	75.4	6.41	0.7	8.3	213
	3	8/25/01	10:20	23.2	1430	74	6.30	1.2	8.3	214
	3	8/25/01	10:20	23.2	1430	73.9	6.29	1.9	8.2	217
	3	8/25/01	10:21	23.1	1432	70.5	6.01	2.7	8.2	222
	3	8/25/01	10:21	23.0	1432	62.6	5.35	3.0	8.1	216
	3	8/25/01	10:21	23.0	1433	57.4	4.90	3.0	8.1	200
	1	9/22/01	10:51	19.0	1498	62.4	5.76	0.6	7.6	131
	1	9/22/01	10:51	19.0	1497	66.7	6.17	0.6	7.5	149
	1	9/22/01	10:51	19.0	1500	**186.7 c**	**17.26 c**	1.4	7.5	161
	1	9/22/01	10:51	19.0	1501	72.9	6.74	1.3	7.6	162
	1	9/22/01	10:52	19.0	1495	**243.6 a**	**22.51 a**	1.8	7.6	164
	1	9/22/01	10:52	19.0	1499	78.4	7.25	2.0	7.6	169
	1	9/22/01	10:53	19.0	1505	88.7	8.20	3.3	7.7	177
	2	9/22/01	11:11	18.8	1508	149.2	13.84	0.5	7.9	169
	2	9/22/01	11:11	18.8	1508	149.2	13.84	0.5	7.9	169
	2	9/22/01	11:12	18.8	1511	**219.1 a**	**20.33 a**	1.2	7.9	182
	2	9/22/01	11:14	18.8	1521	77.2	7.16	1.6	8.0	186
	2	9/22/01	11:14	18.8	1521	77.2	7.16	1.6	8.0	186
	2	9/22/01	11:14	18.8	1521	77.2	7.16	1.6	8.0	186
	2	9/22/01	11:14	18.8	1521	77.2	7.16	1.6	8.0	186
	3	9/22/01	11:34	**15.6 d**	**9 d**	**-13.1 b**	**-1.31 b**	0.0	**7.2 d**	225
	3	9/22/01	11:34	18.7	1520	93.1	8.64	0.5	8.0	174
	3	9/22/01	11:34	18.7	1518	**245.2 a**	**22.76 a**	0.8	8.0	179
	3	9/22/01	11:35	18.7	1519	94.9	8.82	0.9	8.0	166
	3	9/22/01	11:35	18.7	1519	94.9	8.82	0.9	8.0	166
	1	10/8/01	9:31	14.2	1499	**194.6 d**	**19.89 d**		8.3	
	1	10/8/01	9:32	14.1	1503	**216.8 d**	**22.19 d**		8.2	

North Sterling Reservoir	1	10/8/01	9:32	14.1	1498	**218.4 d**	**22.36 d**		8.4	
	1	10/8/01	9:32	14.0	1503	**217.9 d**	**22.34 d**		8.4	
	1	10/8/01	9:32	14.0	1501	**208.8 d**	**21.42 d**		8.4	
	1	10/8/01	9:33	14.0	1504	**200.2d**	**20.54 d**		8.4	
	1	10/8/01	9:33	14.0	1504	**198.6 d**	**20.38 d**		8.4	
	1	10/8/01	9:33	14.0	1506	**185.3 d**	**19.01 d**		8.3	
	1	10/8/01	9:33	14.0	1505	**182.1 d**	**18.69 d**		8.2	
	2	10/8/01	9:43	14.0	144	**246.1 d**	**25.34 d**		8.7	
	2	10/8/01	9:44	14.0	111	**274 d**	**28.23 d**		8.6	
	2	10/8/01	9:44	13.9	106	**273.7 d**	**28.30 d**		8.6	
	3	10/8/01	9:54	13.5	201	**212.6 d**	**22.14 d**		8.9	
	3	10/8/01	9:54	13.3	133	**219 d**	**22.90 d**		8.6	
	3	10/8/01	9:55	13.5	156	**213.1 d**	**22.21 d**		8.7	
	3	10/8/01	9:55	13.5	134	**206.8 d**	**21.54 d**		8.8	
Prewitt Reservoir	4	4/10/01	13:02	10.6	1477	100.5	11.14	0.3	9.0	251
	4	5/12/01	13:41	14.6	1459	122.2	12.39	1.3	8.9	192.7
	4	6/7/01	12:23	20.4	1419	112.8	10.13	0.5	8.8	200
	4	6/21/01	13:12	25.5	1473	109.5	8.93	0.0	9.1	193.3
	4	7/5/01	11:30	23.8	1511	110.9	9.33	0.6	8.7	246
	4	7/19/01	11:37	26.9	1462	123.3	9.81	0.7	9.0	178
	4	8/2/01	11:43	25.5	1439	118.5	9.66	0.0	9.1	180
	4	8/25/01	11:45	23.0	1494	128.7	10.98	0.1	8.9	176
	4	9/22/01	13:54	22.7	1542	154.4	13.27	0.0	9.3	168
	4	10/8/01	11:18	15.7	980	**21 d**	**2.08 d**		8.3	
Jackson Reservoir	dock	4/10/01	14:29	9.8	1272	90.2	10.20	0.0	9.0	234
	5	5/12/01	15:26	14.6	1253	113.1	11.47	1.3	8.8	224.7
	5	5/12/01	15:29	13.3	1284	98.4	10.26	3.0	8.7	197.7
	5	5/12/01	15:28	11.7	1296	113.6	12.26	5.0	8.3	207.3
	6	5/12/01	16:00	14.5	1283	133	13.52	1.7	8.9	220.8
	6	5/12/01	16:03	12.9	1288	92.4	9.72	3.5	8.6	229.1
	7	5/12/01	16:10	13.5	1286	106.9	11.10	1.7	8.7	241.6
	7	5/12/01	16:12	11.2	1299	44.3	4.84	3.4	8.1	254.7
	5	6/7/01	14:35	21.8	1274	98.2	8.58	0.8	8.6	187
	5	6/7/01	14:36	19.6	1286	93.1	8.51	1.5	8.5	191
	5	6/7/01	14:36	19.0	1287	84.8	7.84	2.1	8.5	196
	5	6/7/01	14:36	18.7	1286	79.4	7.39	2.5	8.4	199
	5	6/7/01	14:37	18.4	1288	72.1	6.74	2.8	8.3	202
	5	6/7/01	14:37	18.3	1289	64.8	6.08	3.5	8.3	205
	5	6/7/01	14:37	18.2	1290	61.1	5.74	3.9	8.2	207
	5	6/7/01	14:38	18.0	1289	56.7	5.35	4.6	8.2	210
	5	6/7/01	14:38	17.6	1294	47.3	4.50	5.0	8.0	212
	6	6/7/01	15:09	21.5	1279	133.4	11.74	0.8	8.7	170
	6	6/7/01	15:10	21.3	1281	115.1	10.17	1.0	8.7	183
	6	6/7/01	15:11	20.3	1282	109.9	9.89	2.0	8.6	187
	6	6/7/01	15:11	19.3	1276	103	9.45	3.1	8.5	193

Jackson Reservoir	6	6/7/01	15:12	18.0	1284	73.4	6.92	3.8	8.3	200
	7	6/7/01	15:18	19.9	1284	94.3	8.55	0.9	8.5	199
	7	6/7/01	15:18	19.7	1273	95.1	8.67	1.2	8.5	200
	7	6/7/01	15:18	18.2	1279	88	8.27	2.0	8.4	204
	7	6/7/01	15:19	17.4	1281	71.7	6.84	2.9	8.3	209
	7	6/7/01	15:19	17.1	1283	61.8	5.94	3.6	8.2	212
	5	6/21/01	14:54	24.6	10	87.1	7.25	-0.1	**7.7 d**	200.5
	5	6/21/01	15:04	24.1	1323	90.5	7.58	0.4	8.8	129.5
	5	6/21/01	15:05	22.9	1314	94.9	8.13	1.0	8.9	136.2
	5	6/21/01	15:05	21.1	1316	95.2	8.45	1.6	8.9	145
	5	6/21/01	15:06	20.3	1321	77.2	6.95	2.3	8.7	154.6
	5	6/21/01	15:07	20.1	1323	64.7	5.85	3.0	8.6	162.7
	6	6/21/01	15:13	**21. d0**	1372	66.6	5.92	0.0	**8.2 d**	200.6
	6	6/21/01	15:13	21.4	1315	86.9	7.66	0.8	8.8	173.1
	6	6/21/01	15:14	20.1	1316	86.9	7.86	1.5	8.8	171.5
	6	6/21/01	15:14	19.9	1320	84	7.62	1.6	8.8	173
	6	6/21/01	15:14	19.6	1322	74.2	6.77	2.2	8.7	176.8
	6	6/21/01	15:15	19.6	1322	69.7	6.37	2.7	8.7	179.3
	6	6/21/01	15:15	19.4	1324	60	5.50	3.0	8.6	182.9
	6	6/21/01	15:16	19.4	1324	58.4	5.36	3.7	8.5	185.6
	7	6/21/01	15:21	**21.8 c**	1378	68.7	6.01	0.1	**8.5 c**	194.9
	7	6/21/01	15:21	22.7	1338	83.8	7.20	0.3	8.7	179
	7	6/21/01	15:22	22.2	1319	92.5	8.03	0.6	8.8	177.2
	7	6/21/01	15:22	20.0	1318	100.7	9.12	1.4	8.8	179.4
	7	6/21/01	15:23	19.3	1321	94	8.63	2.1	8.7	182.7
	7	6/21/01	15:23	19.0	1324	82.6	7.63	2.7	8.7	186.3
	7	6/21/01	15:24	18.8	1328	62.1	5.77	3.0	8.5	190.4
	5	7/5/01	14:07	25.3	1319	121.4	9.95	0.9	8.4	97
	5	7/5/01	14:07	25.2	1330	119.9	9.83	1.1	8.5	114
	5	7/5/01	14:08	25.2	1339	119.5	9.80	1.4	8.6	122
	6	7/5/01	14:21	24.3	1350	118	**9.83 c**	0.6	8.5	152
	6	7/5/01	14:22	24.3	1352	93.3	7.79	0.6	8.5	156
	6	7/5/01	14:22	24.2	1351	90.9	7.59	1.2	8.5	160
	6	7/5/01	14:22	24.2	1351	90.3	7.55	1.6	8.5	165
	6	7/5/01	14:23	24.1	1351	87.4	7.32	2.4	8.4	168
	6	7/5/01	14:23	24.0	1353	82.8	6.95	3.0	8.4	169
	7	7/5/01	14:30	24.7	1338	102.8	8.52	0.5	8.6	146
	7	7/5/01	14:30	24.5	1342	99.4	8.26	0.8	8.6	154
	7	7/5/01	14:31	24.5	1342	98.4	8.18	1.4	8.5	159
	7	7/5/01	14:31	24.4	1343	92.5	7.70	2.3	8.5	165
	5	7/19/01	13:40	28.0	1250	152.1	11.87	0.3	8.9	154
	5	7/19/01	13:40	27.4	1255	164.2	12.94	0.6	9.0	167
	5	7/19/01	13:40	26.1	1258	124.3	10.04	1.3	8.8	179
	5	7/19/01	13:41	25.1	1265	82.2	6.76	2.0	8.5	189
	5	7/19/01	13:41	24.3	1275	33.8	2.82	2.7	8.2	199

Jackson Reservoir	5	7/19/01	13:42	24.1	1280	12.4	1.04	3.6	8.0	164
	5	7/19/01	13:42	24.0	1286	6.9	0.58	3.6	7.9	66
	6	7/19/01	13:47	26.4	1281	129	10.36	0.3	8.8	147
	6	7/19/01	13:47	26.5	1274	155.1	12.42	0.5	9.0	159
	6	7/19/01	13:47	26.0	1260	156.4	12.65	1.0	9.0	166
	6	7/19/01	13:48	24.6	1269	120.2	9.97	2.0	8.8	179
	6	7/19/01	13:49	24.2	1273	88.9	7.42	2.8	8.6	191
	7	7/19/01	13:58	25.3	1305	99.3	**8.14 d**	0.1	8.6	209
	7	7/19/01	13:58	26.6	1248	198.6	15.89	0.5	9.2	184
	7	7/19/01	13:59	26.5	1236	204.9	16.43	0.7	9.2	184
	7	7/19/01	13:59	25.8	1236	180.6	14.67	1.3	9.1	190
	7	7/19/01	14:00	24.9	1242	135.6	11.18	1.7	8.9	199
	7	7/19/01	14:00	24.5	1249	136.2	11.32	2.4	8.7	206
	7	7/19/01	14:00	23.8	1264	48.3	4.07	2.7	8.3	197
	7	7/19/01	14:01	**23.7 c**	1271	41	3.46	2.6	**8.2 c**	172
	5	8/2/01	13:27	28.5	1308	116.3	8.99	0.1	8.8	148
	5	8/2/01	13:28	28.7	1308	120.6	9.30	0.1	8.8	164
	5	8/2/01	13:28	27.1	1295	117.7	9.32	0.6	8.9	175
	5	8/2/01	13:29	25.9	1300	85.5	6.93	1.2	8.8	189
	5	8/2/01	13:29	25.5	1300	63.6	5.19	1.7	8.6	198
	5	8/2/01	13:29	25.4	1301	50.6	4.14	2.2	8.5	202
	6	8/2/01	13:37	27.9	1306	128.7	10.06	0.2	8.8	182
	6	8/2/01	13:37	27.9	1307	108.6	8.49	0.2	8.9	189
	6	8/2/01	13:38	25.6	1302	96.3	7.84	0.9	8.9	198
	6	8/2/01	13:38	24.9	1301	66.1	5.45	1.6	8.7	207
	6	8/2/01	13:39	24.8	1303	56.4	4.67	2.0	8.6	212
	6	8/2/01	13:39	24.7	1302	46.4	3.84	2.0	8.5	163
	6	8/2/01	13:40	24.7	1303	51.5	4.26	2.1	8.5	164
	7	8/2/01	13:45	28.1	1310	119.2	9.28	0.2	8.8	164
	7	8/2/01	13:46	28.2	1310	112.9	8.78	0.2	8.9	170
	7	8/2/01	13:46	27.0	1284	113.8	9.03	0.7	8.9	176
	7	8/2/01	13:46	25.0	1298	83.8	6.90	1.0	8.8	187
	7	8/2/01	13:47	24.6	1301	74.5	6.17	1.7	8.6	195
	7	8/2/01	13:47	**24.5 c**	1302	46.7	3.88	1.6	**8.5 c**	160
	7	8/2/01	13:48	**24.6 c**	1302	54.5	4.53	1.3	**8.5 c**	162
	Shore	8/25/01	13:04	24.0	1380	121.8	10.21	-0.1	9.0	184
	Shore	9/22/01	15:31	22.8	1566	114.7	9.83	-0.1	9.3	167
	Shore	10/8/01	12:40	20.8	1567	137.6	12.27		8.5	

Data points not used in graphs calculations: (a) = sudden increase in value; (b) = negative concentration; (c) = two values at a similar depth (within 0.5 meters); (d) = questionable value.

Appendix C.2 Secchi Depth Measurements

North Sterling Reservoir			Jackson Reservoir			Prewitt Reservoir		
Site No	Date	Secchi Depth (m)	Site No	Date	Secchi Depth (m)	Site No	Date	Secchi Depth (m)
Dock	4/10/01	0.65	dock	4/10/01	0.30	4	4/10/01	0.40
2	5/12/01	0.52	5	5/12/01	0.41	4	5/12/01	0.40
3	5/12/01	0.43	5	6/7/01	0.61	4	6/7/01	0.30
1	6/7/01	0.88	6	6/7/01	0.76	4	6/20/01	0.40
2	6/7/01	0.58	7	6/7/01	0.88	4	7/5/01	0.27
1	6/21/01	0.79	5	6/21/01	0.68	4	7/19/01	0.30
2	6/21/01	0.73	6	6/21/01	0.62	4	8/2/01	0.15
3	6/21/01	1.28	7	6/21/01	0.62	4	8/25/01	0.18
1	7/5/01	0.88	5	7/5/01	0.40	4	9/22/01	0.18
2	7/5/01	0.79	6	7/5/01	0.46	4	10/8/01	0.28
3	7/5/01	0.70	7	7/5/01	0.37			
1	7/19/01	0.70	5	7/19/01	0.61			
2	7/19/01	0.52	6	7/19/01	0.49			
3	7/19/01	0.49	7	7/19/01	0.55			
1	8/2/01	0.70	5	8/2/01	0.46			
2	8/2/01	0.49	6	8/2/01	0.52			
3	8/2/01	0.40	7	8/2/01	0.49			
1	8/25/01	0.49	Shore	8/25/01	0.18			
2	8/25/01	0.34	Shore	9/22/01	na			
3	8/25/01	0.27	Shore	10/8/01	na			
1	9/22/01	0.46						
2	9/22/01	0.30						
3	9/22/01	0.27						
1	10/8/01	0.37						
2	10/8/01	0.37						
3	10/8/01	0.27						

Appendix C.3 CSU Soil, Water and Plant Testing Lab Dataset

Note: Removed Data Points are in *Italics*
Duplicate samples are in **Bold**

Reservoir	Site No	Date M/D/Y	Sample ID #	S/D *	TKN mg/L	NH$_4$ mg/L	NH$_4$-N mg/L	NO$_3$ mg/L	NO$_3$-N mg/L	Total P mg/L	Ortho P mg/L	NO$_2$	NO$_2$-N	Depth **
Jackson	**dock**	**4/10/01**	**WRN-PLK-03**	**S**	**5.6**	**1**	**0.8**	**11.9**	**2.7**	**0.35**				**S**
Jackson	**dock**	**4/10/01**	**WRN-PKL-05**	**D**	**4.6**	**1**	**0.8**	**11.9**	**2.7**	**0.37**				**S**
Jackson	5	5/12/01	WRN-SIC-03	S	2.4	1	0.8	7.1	1.6	0.203	0.021			S
Jackson	5	5/12/01	WRNL-SIC-03	S	2.9	0.80	0.62	8.4	1.9	0.231	0.018			5 m
Jackson	5	6/7/01	WRN-RNY-03	S	1.8	0.1	0.1	5.3	1.2	0.233	0.024	<0.1	<0.1	S
Jackson	5	6/7/01	WRN-RNY-05	S	2.1	0.3	0.2	5.3	1.2	0.266	0.022	<0.1	<0.1	3 m
Jackson	5	6/7/01	WRN-RNY-06	S	1.3	0.3	0.2	5.3	1.2	0.286	0.029	<0.1	<0.1	5 m
Jackson	**5**	**6/21/01**	**WRN-SML-06**	**S**	**0.8**	**< 0.1**	**< 0.1**	**4**	**0.9**	**0.091**	**0.001**	**0.3**	**0.1**	**S**
Jackson	**5**	**6/21/01**	**WRN-SML-07**	**D**	**0.7**	**< 0.1**	**< 0.1**	**4**	**0.9**	**0.089**	**0.001**	**0.3**	**0.1**	**S**
Jackson	**5**	**7/5/01**	**WRN-FRE-03**	**S**	**1.4**	**0.8**	**0.6**	**2.7**	**0.6**	**0.158**	**0.083**			**S**
Jackson	**5**	**7/5/01**	**WRN-FRE-04**	**D**	**1.5**	**0.9**	**0.7**	**2.7**	**0.6**	**0.162**	**0.086**			**S**
Jackson	5	7/19/01	WRN-MOM-3	S	1.7	<0.1	< 0.1	< 0.1	< 0.1	0.142	0.005	<0.3	<0.1	S
Jackson	5	8/2/01	WRN-ATS-02	S	1.7	0.3	0.2	0.4	0.1	0.169	0.009			S
Jackson	shore	8/25/01	WRN-STE-04	S	2.1	0.4	0.3	0.4	0.1	0.212	0.137			S
Jackson	shore	9/22/01	WRN-RAB-4	S	6.2	1.6	1.2	< 0.4	< 0.1	0.650	0.068			S
Jackson	shore	10/8/01	WRN-END-02	S	4.1	0.7	0.5	1.8	0.4	0.409	0.121			S
Prewitt	4	4/10/01	WRN-PKL-02	S	5.5	1	0.8	6.2	1.4	0.31				S
Prewitt	4	5/12/01	WRN-SIC-02	S	3.4	0.41	0.32	< 0.4	< 0.1	0.201	0.001			S
Prewitt	4	6/7/01	WRN-RNY-02	S	3	0.1	0.1	0.9	0.2	0.315	0.068	< 0.1	< 0.1	S
Prewitt	4	6/20/01	WRN-SML-05	S	1.8	< 0.1	< 0.1	0.4	0.1	0.182	0.002	< 0.1	< 0.1	S
Prewitt	4	7/5/01	WRN-FRE-02	S	1.6	0.6	0.5	< 0.1	< 0.1	0.173	0.146			S
Prewitt	4	7/19/01	WRN-MOM-4	S	2.2	<0.1	< 0.1	< 0.1	< 0.1	0.195	0.021	0.3	0.1	S
Prewitt	4	8/2/01	WRN-ATS-03	S	2.0	0.4	0.3	0.4	0.1	0.223	0.008			S
Prewitt	4	8/25/01	WRN-STE-03	S	3.4	1.4	1.1	1.8	0.4	0.355	0.140			S
Prewitt	4	9/22/01	WRN-RAB-3	S	3.0	< 0.1	< 0.1	< 0.4	< 0.1	0.312	0.016	< 0.3	< 0.1	S

Reservoir	Site No	Date M/D/Y	Sample ID #	S/D *	TKN mg/L	NH$_4$ mg/L	NH$_4$-N mg/L	NO$_3$ mg/L	NO$_3$-N mg/L	Total P mg/L	Ortho P mg/L	NO$_2$	NO$_2$-N	Depth **
Prewitt	4	10/8/01	WRN-END-01	S	3.2	0.1	0.1	2.2	0.5	0.331	0.005	0.3	0.1	S
Sterling	dock	4/9/01	WRN-PKL-01	S	4.1	0.4	0.3	23.4	5.3	0.41				S
Sterling	**2**	**5/12/01**	**WRNU-SIC-01**	**S**	**2.1**	**1.2**	**0.96**	**16.8**	**3.8**	**0.201**	**0.015**			**S**
Sterling	**2**	**5/12/01**	**WRCU-SIC-01**	**D**	**2.2**	**1.4**	**1.1**	**16.4**	**3.7**	**0.189**	**0.013**			**S**
Sterling	2	5/12/01	WRNL-SIC-01	S	1.7	0.70	0.54	17.7	4.0	0.228	0.015			6 m
Sterling	2	5/12/01	WRNG-SIC-01	S	1.8	1.2	0.90	16.4	3.7	0.223	<0.001			8 m
Sterling	1	6/7/01	WRN-RNY-01	S	0.9	< 0.1	< 0.1	14.6	3.3	0.187	< 0.001	< 0.1	< 0.1	S
Sterling	1	6/21/01	WRN-SML-01	S	0.5	< 0.1	< 0.1	11.9	2.7	0.053	< 0.001	0.3	0.1	S
Sterling	1	7/5/01	WRN-FRE-01	S	0.9	0.8	0.6	9.3	2.1	0.090	0.016			S
Sterling	**1**	**7/19/01**	**WRN-MOM-1**	**S**	**1.8**	**< 0.1**	**< 0.1**	**5.3**	**1.2**	**0.179**	**0.003**	**0.3**	**0.1**	**S**
Sterling	**1**	**7/19/01**	**WRN-MOM-2**	**D**	**1.7**	**0.1**	**0.1**	**5.3**	**1.2**	**0.171**	**0.004**	**0.3**	**0.1**	**S**
Sterling	**1**	**8/2/01**	**WRN-ATS-04**	**D**	**1.8**	**0.9**	**0.7**	**4.0**	**0.9**	**0.179**	**0.007**			**S**
Sterling	**1**	**8/2/01**	**WRN-ATS-01**	**S**	**1.9**	**0.9**	**0.7**	**4.0**	**0.9**	**0.188**	**0.007**			**S**
Sterling	**1**	**8/25/01**	**WRN-STE-01**	**S**	**1.6**	**0.4**	**0.3**	**4.4**	**1.0**	**0.159**	**0.075**			**S**
Sterling	**1**	**8/25/01**	**WRN-STE-02**	**D**	**1.8**	**0.7**	**0.5**	**4.0**	**0.9**	**0.178**	**0.075**			**S**
Sterling	**1**	**9/22/01**	**WRN-RAB-1**	**S**	**2.1**	**0.4**	**0.3**	**0.4**	**0.1**	**0.190**	**0.009**	**0.3**	**0.1**	**S**
Sterling	**1**	**9/22/01**	**WRN-RAB-2**	**D**	**2.5**	**0.5**	**0.4**	**0.8**	**0.2**	**0.248**	**0.019**	**0.3**	**0.1**	**S**
Sterling	**1**	**10/8/01**	**WRN-END-03**	**S**	**2.5**	**0.1**	**0.1**	**< 0.4**	**< 0.1**	**0.249**	**0.020**	**0.3**	**0.1**	**S**
Sterling	**1**	**10/8/01**	**WRN-END-04**	**D**	**2.7**	**< 0.1**	**< 0.1**	**< 0.4**	**< 0.1**	**0.275**	**0.027**	**0.3**	**0.1**	**S**

* S or D in the 5th column differentiates samples from duplicates collected for quality assurance purposes.

** S indicates samples collected within one meter of the surface. If a samples was collected at another depth, the depth in meters is listed.

Appendix C.4 Chlorophyll Results

Note: Duplicate and replicate samples are in **Bold**
Removed Samples are in *Italics*

Reservoir	Chlorophyll Sample		Site No	Date	Chl-a	Chl-b	Chl-c
				M/D/Y	mg/m^3	mg/m^3	mg/m^3
Jackson	***WRC-PKL-03***	***S***	***Dock***	***4/10/01***	***21.79***	***0.91***	***2.32***
Jackson	***WRC-PKL-05***	***LD***	***Dock***	***4/10/01***	***25.88***	***1.06***	***2.74***
Jackson	*WRC-SIC-03*	*S*	*5*	*5/12/01*	*8.11*	*0.75*	*0.78*
Jackson	WRC-RNY-03	S	5	6/7/01	7.4	1.03	0.52
Jackson	WRC-SML-04	S	5	6/21/01	7.56	1.16	0.76
Jackson	WRC-FRE-03	S	5	7/5/01	51.9	3.3	3.5
Jackson	WRC-MOM-03	S	5	7/19/01	28.2	-0.2	2.2
Jackson	WRC-ATS-02	S	5	8/2/01	37.6	3.4	3.3
Jackson	**WRC-STE-02**	**S**	**8**	**8/25/01**	**117.9**	**4.4**	**13.3**
Jackson	**WRC-STE-04**	**D**	**8**	**8/25/01**	**145.3**	**5.7**	**16.3**
Jackson	WRC-RAB-02	S	8	9/22/01	285	25.1	25.1
Jackson	WRC-END-03	S	8	10/8/01	245.3	20.2	21.5
Prewitt	*WRC-PKL-02*	*S*	*4*	*4/10/01*	*14.25*	*0.46*	*2.06*
Prewitt	*WRC-SIC-02*	*S*	*4*	*5/12/01*	*44.9*	*-1.07*	*2.95*
Prewitt	**WRC-RNY-02**	**S**	4	**6/7/01**	**156.3**	**0.3**	**8.62**
Prewitt	**WRC-RNY-04**	**LD**	4	**6/7/01**	**179**	**0.37**	**10.42**
Prewitt	WRC-RNY-04	LD(BOR)	4	6/7/01	183	0.45	10.67
Prewitt	**WRC-SML-02**	**S**	4	**6/20/01**	**100.39**	**0.06**	**5.92**
Prewitt	**WRC-SML-03**	**D**			**107.26**	**0.4**	**6.9**
Prewitt	WRC-FRE-02	S	4	7/5/01	127.3	-2.7	4.9
Prewitt	WRC-MOM-02	S	4	7/19/01	80.9	-2.5	2.4
Prewitt	WRC-ATS-03	S	4	8/2/01	207	-2	11
Prewitt	WRC-STE-03	S	4	8/25/01	307	9.7	22.5
Prewitt	**WRC-RAB-03**	**S**	4	**9/22/01**	**173.7**	**-2.2**	**11.7**
Prewitt	**WRC-RAB-04**	**D**	4	**9/22/01**	**191.4**	**-1.9**	**10.9**
Prewitt	**WRC-END-02**	**S**	4	**10/8/01**	**97.1**	**0.1**	**5.2**
Prewitt	**WRC-END-04**	**LD**	4	**10/8/01**	**101.6**	**0.0**	**5.5**
Sterling	*WRC-PKL-01*	*S*		*4/10/01*	*5.34*	*0.15*	*0.57*
Sterling	WRC-RNY-01	S	1	6/7/01	42.8	2.06	3.12
Sterling	WRC-SML-01	S	1	6/21/01	26.87	3.63	2.55
Sterling	WRC-FRE-01	S	1	7/5/01	33.6	1.4	2.3
Sterling	WRC-MOM-01	S	1	7/19/01	48.4	4.5	1.6

Sterling	WRC-ATS-01	S	1	8/2/01	37.7	1.5	2.6
Sterling	WRC-STE-01	S	1	8/25/01	86	3.6	6.5
Sterling	WRC-RAB-01	S	1	9/22/01	80.8	11.8	6.5
Sterling	WRC-END-01	S	1	10/8/01	129.7	8.9	8.1

Pheophytin Results

Reservoir	Date	Location	Chl a (mg/m^3)	Phaeo a (mg/m^3)	Ratio 664/665
			-------------------	-------------------	-------------------
Sterling	4/10/01	Dock	2.16	5.11	1.21
Prewitt	4/10/01	Dock	6.57	12.27	1.24
Jackson	**4/10/01**	**Dock**	**7.74**	**22.68**	**1.18**
Jackson	**4/10/01**	**Dock**	**9.72**	**26.05**	**1.19**
Prewitt	5/12/01	Dock	36.58	11.31	1.53
Jackson	5/12/01	5	6.14	2.95	1.47
Sterling	6/7/01	1	30.44	18.69	1.43
Prewitt	**6/7/01**	**Dock**	**141.83**	**15.09**	**1.63**
Prewitt	**6/7/01**	**Dock**	**165.27**	**13.87**	**1.65**
Jackson	6/7/01	5	6.17	1.78	1.54

Appendix D Total nutrient ~ chlorophyll-*a* models evaluated in the TSI worksheet

Carlson (1977)	$\ln \text{chlorophyll-}a = 1.449(\ln \text{TP})-2.442$
Brown (2000)	$\log \text{chlorophyll-}a = -0.369 + 1.053(\log \text{TP})$
Brown (2000)	$\log \text{chlorophyll-}a = -2.42 + 1.206(\log \text{TN})$
Brown (2000)	$\log \text{chlorophyll-}a = -1.1 + 0.91(\log \text{TP}) + 0.321(\log \text{TN})$
Brown (2000)	$\log \text{chlorophyll-}a = -0.078 - 0.42(\log \text{TP}) + 1.27(\log \text{TP})^2 - 0.32(\log \text{TP})^3$
Dillon & Ringer (1974)	$\log \text{chlorophyll-}a = -1.14 + 1.449(\log \text{TP})$
Jones & Bachman (1976)	$\log \text{chlorophyll-}a = -1.09 + 1.46(\log \text{TP})$
Hoyer (1981)	$\log \text{chlorophyll-}a = -0.77 + 1.24(\log \text{TP})$
Canfield (1983)	$\log \text{chlorophyll-}a = -0.15 + 0.744(\log \text{TP})$
Huber (1982)	$\log \text{chlorophyll-}a = -1.08 + 1.52(\log \text{TP})$
Baker (1981)	$\log \text{chlorophyll-}a = -0.41 + 0.79(\log \text{TP})$
Lambou (1982)	$\log \text{chlorophyll-}a = -0.11 + 0.64(\log \text{TP})$
Canfield (1983)	$\log \text{chlorophyll-}a = -2.99 + 1.38(\log \text{TN})$
Hoyer (1981)	$\log \text{chlorophyll-}a = -1.23 + 0.798(\log \text{TN})$
Smith (1982)	$\log \text{chlorophyll-}a = -2.49 + 0.374(\log \text{TP}) + 0.935(\log \text{TN})$
Canfield (1983)	$\log \text{chlorophyll-}a = -2.49 + 0.269(\log \text{TP}) + 1.06(\log \text{TN})$
Hoyer (1981)	$\log \text{chlorophyll-}a = -1.36 + 1.19(\log \text{TP}) + 0.155 (\log \text{TN})$
Canfield (1983)	$\log \text{chlorophyll-}a = -0.4 + 1.09(\log \text{TP})$
Canfield (1983)	$\log \text{chlorophyll-}a = -2.24 + 1.16 (\log \text{TN})$
Canfield (1983)	$\log \text{chlorophyll-}a = -1.65 + 0.51(\log \text{TP}) + 0.73 (\log \text{TN})$
Brezonik (1983)	$\ln \text{chlorophyll-}a = -2.85 + 1.64(\ln \text{TP})$
Brezonik (1983)	$\ln \text{chlorophyll-}a = 2.97 + 1.48(\ln \text{TN})$
Brezonik (1983)	$\ln \text{chlorophyll-}a = -2.44 + 1.29(\ln \text{TP})$
Brezonik (1983)	$\ln \text{chlorophyll-}a = 2.7 + 1.37(\ln \text{TN})$