Report for 2001SD1821B: Factors Affecting Nutrient Availability and Primary Productivity in Black Hills Reservoirs

- Dissertations:
    - Holcomb, Benjamin. 2002. Nutrient Inputs, Iron Availability and Algal Biomass in Black Hills Watersheds: Implications for Reservoir and Stream Productivity. M.S. Thesis, Wildlife and Fisheries Department, South Dakota State University, Brookings, South Dakota. 98 pp.
- Other Publications:
    - Chipps, Steven R., Benjamin M. Holcomb. 2002. Nutrient Inputs, Iron Availability, and Algal Biomass in Black Hills Reservoirs: Implications for Reservoir Productivity. USGS South Dakota Cooperative Fish and Wildlife Research Unit, Department of Wildlife and Fisheries Sciences, South Dakota State University, Brookings, South Dakota.

Report Follows:

EXECUTIVE SUMMARY

Exchange of phosphorus between sediments and water is a major component of the phosphorus cycle in freshwater lakes. Because of the importance of phosphorus as a limiting nutrient in fresh waters, much interest has been devoted to phosphorus availability in lake sediments and mechanisms that regulate it's movement into the overlying water (Wetzel 2001; Bostrom et al. 1982). In general, sediment phosphorus concentration is only weakly linked to phosphorus concentration in lakes and reservoirs (Scheffer 1998). A variety of factors can regulate phosphorus release from lake sediments and include 1) the ability of sediments to retain phosphorus, 2) conditions of the overlying water and 3) faunal characteristics (e.g., bioturbation) of lake sediments (Wetzel 2001).
In freshwater systems, iron is an important agent that binds phosphorus under aerobic (i.e., oxygenated) conditions. As a result, iron availability and redox condition can have important implications for sediment nutrient concentration in lakes and reservoirs.

Natural bog iron deposits are characteristic features of the upper Rapid Creek watershed in the Black Hills of western South Dakota. To explore relationships among iron availability, nutrient concentrations and algal biomass in Black Hills reservoirs, we quantified limnological characteristics of Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. External phosphorus input (total P) ranged from 0.5 mg $P/m^2/d$ in Deerfield Reservoir to 7.3 mg $P/m^2/d$ in Stockade Reservoir and was poorly related to sediment phosphorus concentration. Although total phosphorus concentration was lowest in Pactola Reservoir ($\bar{x}$=12 µg/L), sediment phosphorus availability was relatively high compared to other reservoirs.

Iron (Fe) inputs varied appreciably across reservoirs, ranging from 5.5 mg $Fe/m^2/d$ in Deerfield Reservoir to 132.4 mg $Fe/m^2/d$ in Pactola Reservoir. Sediment iron availability was significantly higher in Pactola Reservoir ($\bar{x}$=51.5 mg/g) than in other Black Hills reservoirs (overall $\bar{x}$=26.6 mg/g) owing to 1) high Fe loading rates and 2) aerobic conditions in the hypolimnion. Because of high sediment Fe availability, sediment P:Fe ratio in Pactola Reservoir was low ($\bar{x}$=2.5) compared to other reservoirs (overall $\bar{x}$=4.5), implying that under aerobic conditions, Pactola sediments act as a strong buffer to sediment phosphorus release. In reservoirs that experienced summer hypolimnetic anoxia (i.e., Sheridan and Stockade reservoirs), we observed significant increases in

water column phosphorus concentration measured near the sediment-water interface, underlying the importance of redox potential on internal phosphorus loading in Black Hills reservoirs.

Phosphorus loading rates provided reasonable estimates of nutrient concentration in Black Hills reservoirs. As a result, mass-balance models should prove useful for addressing effects of external phosphorus inputs on reservoir nutrient levels. Factors known to affect internal nutrient loading, however, varied appreciably across reservoirs. Using multiple regression analysis, we developed an empirical model for predicting reservoir nutrient concentration that incorporated measures of 1) sediment P availability, 2) sediment Fe concentration and 3) redox potential. This model explained about 80% of the variation in hypolimnetic phosphorus concentration and should prove useful for modeling effects of hypolimnetic conditions (e.g., anoxia) on nutrient availability in Black Hills reservoirs.

Total zooplankton density was lowest in Pactola Reservoir ($\bar{x}$=51.4/L) and highest in Stockade Reservoir ($\bar{x}$=187.7/L). Copepods were a dominant component of the zooplankton community in Pactola and Deerfield reservoirs, comprising about 60 percent of total zooplankton biomass. Moreover, the cladoceran community in Pactola and Deerfield reservoirs was dominated by *Daphnia galeata mendotae*, whereas in Sheridan and Stockade reservoirs, *D. pulex* was the dominant grazer. We postulate that differences in *Daphnia* composition likely reflect a combination of reservoir productivity and predation pressure by zooplanktivorous fishes. As a larger cladoceran, *D. pulex* is generally regarded as a more efficient filter feeder than *D. mendotae,* but is also more susceptible to fish predation. In general, abundance of herbivorous zooplankton appeared to have little affect (i.e., grazing pressure) on water transparency in Black Hills reservoirs. Rather, biomass of primary consumers was positively correlated to algal abundance in Black Hills reservoirs.

INTRODUCTION

Trophic status and productivity vary considerably among Black Hills reservoirs in western South Dakota (German 1997). Differences in reservoir productivity can be attributed to several factors that include 1) basin morphology, 2) nutrient availability, 3) flushing rate, 4) sediment redox potential, and 5) food web structure. Summer water transparency, for example, ranges from a low of 0.6 m in Stockade Reservoir to a high of 9 m in Pactola Reservoir, with Sheridan and Deerfield reservoirs exhibiting intermediate water clarity (3 and 5 m respectively). In general, nutrient availability and algal biomass are lowest in Pactola Reservoir (total phosphorus=0.010 mg/L; chlorophyll-a=2.9 µg/L) and highest in Stockade Reservoir (0.080 mg/L; 32.9 µg/L; German 1997).

Pactola and Deerfield reservoirs are U.S. Bureau of Reclamation projects that provide important sources of domestic and agricultural water supplies for the region. Water quality in these reservoirs is considered very good with high transparency and relatively low algal biomass (German 1997). Factors that regulate nutrient availability and primary productivity in Black Hills Reservoirs, however, are not well understood. Natural iron deposits occur throughout the upper Rapid Creek watershed (see Appendix A). While considered a local water quality problem, high iron content in downstream water may be important in limiting phosphorus availability, particularly in Pactola Reservoir. Under aerobic conditions, iron is the most important agent immobilizing dissolved, reactive phosphorus in aquatic environments. When productivity and microbial decomposition increase, the hypolimnion of lakes and reservoirs can become anoxic (e.g., low redox potential). When this occurs, iron Fe^{+++} is reduced to Fe^{++} and both iron and phosphorus are released into solution contributing to increased reservoir nutrient concentrations and increased productivity (i.e., internal nutrient loading). Hence, redox conditions at the sediment-water interface play an important role in regulating phosphorus availability and may have important implications for maintaining water quality in Black Hills reservoirs.

Sheridan and Stockade reservoirs are managed by the State of South Dakota and provide important regional recreation opportunities. Both reservoirs may be particularly susceptible to 'internal' nutrient loading because the hypolimnion in these systems often becomes anoxic in summer months (German 1997). Moreover, these reservoirs are located in different watersheds than Pactola and Deerfield reservoirs and generally exhibit higher nutrient concentrations.

Biological communities of lakes and reservoirs can also have an important influence on algal biomass and resulting water quality (Carpenter et al. 1985). Food web structure, for example, can play an important role in regulating the abundance and composition of phytoplankton. Large, herbivorous zooplankton such as *Daphnia*, often play an important role in regulating algal biomass. Zooplanktivorous fishes can significantly reduce *Daphnia* abundance -- an effect that can lead to increased algal biomass and reduced water quality (Carpenter et al. 1985). As a result, trophic interactions may play an important role in regulating algal biomass in lakes and reservoirs. In Black Hills reservoirs, fish community composition varies considerably -- from predominantly warm water fishes in Sheridan and Stockade reservoirs (e.g., centrarchid and percid assemblages) to coolwater fishes in Pactola and Deerfield (e.g., salmonids). While fish abundance and composition are well documented for Black Hills reservoirs, species composition and size structure of planktonic zooplankton are poorly understood. Information on relative abundance and size structure of zooplankton populations can provide important information regarding the potential impacts from planktivorous fishes that influence algal biomass and resulting water quality.

RESEARCH OBJECTIVES

The goals of this study are to explore relationships among iron concentrations, nutrient availability, algal biomass and zooplankton abundance in four, Black Hills reservoirs (Pactola, Deerfield, Sheridan and Stockade). Specific objectives are to 1) quantify seasonal nutrient availability and phytoplankton biomass, 2) quantify phosphorus and iron availability in reservoir sediments, 3) determine phosphorus and iron loading rates, and 4) measure species composition and size structure of planktonic zooplankton in Black Hills Reservoirs.

STUDY AREA

Four major reservoirs occur within the Black Hills of western South Dakota: Pactola, Deerfield, Sheridan, and Stockade. Pactola is the largest and deepest reservoir at 318 ha (max depth=48 m) whereas Stockade is the smallest reservoir at 49 ha (max depth= 15.2 m). Deerfield and Sheridan reservoirs are comparable in size at about 160 ha and maximum depths of about 21 m. Pactola Reservoir is characterized as a meso-oligotrophic reservoir with water transparency often reaching 9 m and summer total phosphorus concentrations of 0.007 mg/L (German 1997). Deerfield reservoir is primarily mesotrophic (total phosphorus = 0.011 mg/L), whereas Sheridan (total phosphorus=0.032 mg/L) and Stockade reservoirs (total phosphorus=0.124 mg/L) are characterized as eutrophic systems (German 1997).

METHODS

Seasonal Nutrient Availability and Algal Biomass

Black Hills reservoirs were sampled seasonally (i.e., 3-4 month intervals) from October 2000 through October 2001. We sampled five sites in each reservoir, except in February when three sites per reservoir were sampled through the ice (Appendix B). At each site, we collected two water samples for analysis of total phosphorus and chlorophyll *a* concentration. Water samples were collected at the surface and 1 m above the sediments at each site using a 2 L Kemmerer bottle. Water samples for total phosphorus analysis were transferred to clean, 250 ml Nalgene bottles and frozen for later analysis (SDSU Water Resources Laboratory). Chlorophyll *a* samples were collected by filtering 250 ml of water through a GF/F filter, wrapping filters in aluminum foil, then freezing filters for later analysis. Chlorophyll *a* was measured using a Turner Design TD-700 fluorometer after 24 h of extraction in 90% acetone. We measured water quality characteristics at 0.5-1.5 m intervals from the deepest site in each reservoir using a YSI DataSonde Model 650. Parameters measured by the DataSonde included dissolved oxygen, temperature, pH, redox potential, specific conductivity, total dissolved solids, ammonia, nitrate, and turbidity (Appendix C). Secchi disk readings were also recorded at reservoir sites where vertical profiles were taken.

External Phosphorus and Iron Inputs

We measured external P and Fe inputs for each reservoir during June-July, 2001. Data on reservoir inflows and outflows were combined with information on phosphorus and iron concentrations measured at stations above and below each reservoir. Water samples collected for iron measurements were stored in 500 ml bottles and fixed with 5 ml of nitric acid. Samples for phosphorus concentration were collected and analyzed as previously described. Inflow and outflow discharge was calculated from 1) mean depths and water velocities measured at each station or 2) data obtained from USGS and/or U.S. Bureau of Reclamation gauging stations. Sampling occurred weekly from early June through July (8 weeks). Areal loading rates for P and Fe were calculated by dividing mean daily inputs (kg/d) by the area of the reservoir. We modeled reservoir phosphorus concentration using the Dillon-Rigler mass-balance model (1974) because it has been successfully used to predict phosphorus concentrations in western reservoirs (Mueller 1982). The equation used to model reservoir phosphorus concentration was:

$$P = L\ \tau/z\ (1-R)$$

where P is reservoir phosphorous concentration (mg/L), L is areal annual phosphorus loading rate (g $P/m^2/y$), τ = hydraulic residence time (y), z = mean depth (m), and R = fractional phosphorus retention. Phosphorus retention (R) was estimated as:

$$R = 1 - (q_o\,[P]_o / \sum q_i\,[P]_{i.}\,,$$

where q_o = outflow discharge volume (m^3/y), $[P]_o$ = outflow P concentration (mg/L), q_i = inflow volume (m^3/y), and $[P]_i$ = inflow P concentration (mg/L) (Dillon and Rigler 1974; Mueller 1982).

Sediment Phosphorus and Iron Availability

The ratio of sediment phosphorus-to-iron (P:Fe) can provide important information about phosphorus storage potential in lakes and reservoirs (Jensen et al. 1992; Sondergaard 1993; van der Molen and Boers 1994). Under aerobic conditions, Fe binds about 10% of its own weight in phosphorus (Scheffer 1998). Hence, knowledge of sediment P:Fe ratios can provide important insight regarding nutrient buffering capacity of lake sediments. Under anaerobic conditions (i.e., reducing environment) Fe^{+++} is reduced to Fe^{++}, effectively releasing P from the sediments and contributing to increased nutrient levels (referred to as internal nutrient loading).

Because the upper Rapid Creek drainage contains several natural bog-iron deposits, we postulated that Fe availability in Pactola Reservoir would be relatively high compared to other reservoirs. To quantify sediment P:Fe ratios, we collected core samples from mid-reservoir sites seasonally from October 2000 to October 2001. Three replicate core samples were collected from each reservoir using a 73 cm weighted coring device (Wildco corer, Wildco Corporation). Sediment cores were extruded from the coring device using a stainless steel plunger and the upper 6 cm layer was extracted and frozen for later processing. Composite sediment samples from the upper 6 cm layer were then homogenized, dried to a constant weight at 60°C, and analyzed for iron (mg/g) and total phosphorus (mg/g) content by South Dakota State University Soils Testing Laboratory, Brookings, South Dakota.

Zooplankton Composition and Size Structure

At each reservoir site, three zooplankton samples were obtained from the upper 5 m using a vertically towed 10 cm Wisconsin net with 63-µm mesh. All zooplankton were preserved in 10 % Lugol's solution and transported to the laboratory for identification and enumeration. In the laboratory, zooplankton were sub sampled by quantifying all zooplankton in 10% sub samples. Zooplankton were identified, counted and 30 individuals of each species measured for total length (mm) to determine density, species composition, size structure, and biomass of the population (Pennak 1989). Individual mass -- estimated using length-weight regression equations (Dumont et. al. 1975) – was multiplied by taxa-specific density to obtain biomass estimates. Differences in total crustacean zooplankton abundance, species composition, size structure, and biomass were determined using analysis of variance (SAS Institute Inc. 1999).

RESULTS & DISCUSSION

Seasonal Nutrient Availability and Algal Biomass

Bivariate plots of Secchi depth versus chlorophyll *a* biomass revealed that water transparency was inversely related to algal biomass in Black Hills reservoirs (Figure 1; Table 1). Mean annual Secchi depths ranged from 2 m in Stockade Reservoir to 8 m in Pactola Reservoir and were similar to values reported by German (1997). Similarly, mean annual chlorophyll *a* biomass was lowest in Pactola Reservoir ($\bar{x}$=0.6 µg/L) and highest in Stockade Reservoir ($\bar{x}$=7.0 µg/L; Table 1). Chlorophyll *a* biomass was

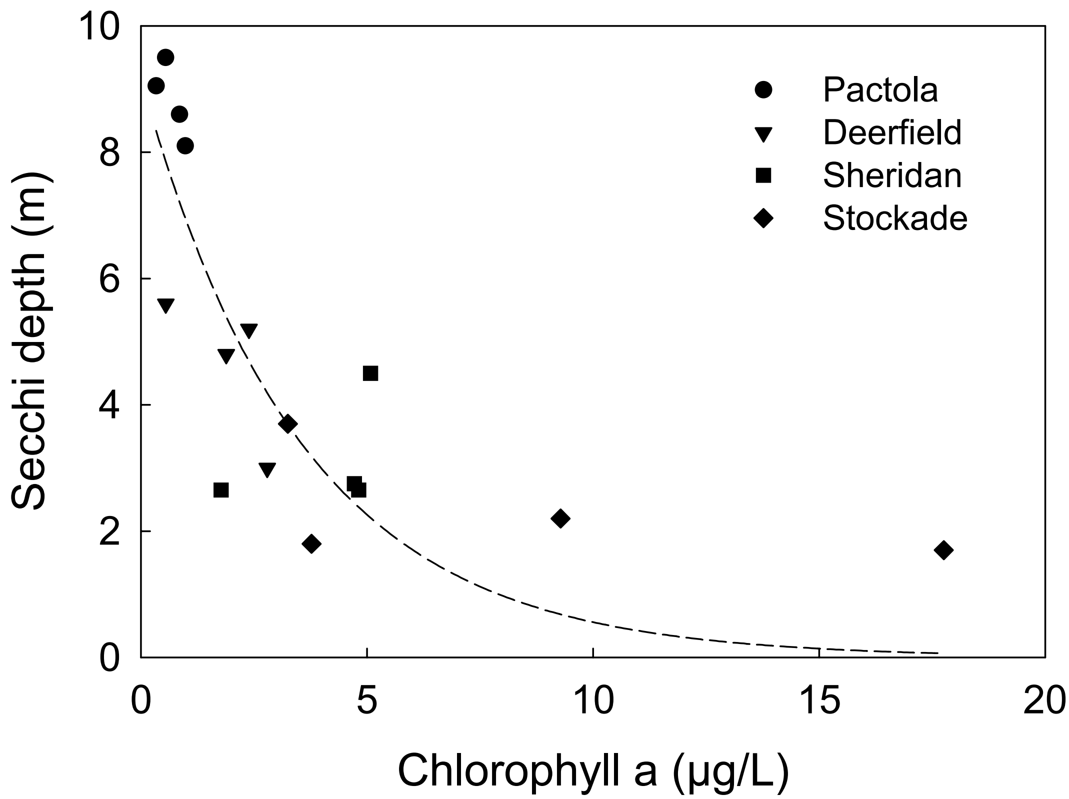

Figure 1. Relationship between Secchi depth and surface algal biomass (chlorophyll a) in Pactola, Deerfield, Sheridan, and Stockade reservoirs, October 2000 to October 2001. Regression line was fitted to the equation, Secchi depth= 9.17e-0.28CHLa (r2= 0.69, P< 0.001).

Table 1. Mean Secchi depth and chlorophyll *a* concentration measured in Black Hills reservoirs from October 2000 to October 2001. Chlorophyll *a* samples were taken 1 m below the surface and 1 m above the bottom. Values in parentheses represent 1 SE.

Reservoir	Sample date	n	Secchi depth (m)	Surface chlorophyll a (µg/L)	Bottom chlorophyll a (µg/L)
Pactola	Oct. 2000	5	9.1	0.34 (0.05)	0.17 (0.02)
	Feb. 2001	3	-	0.40 (0.11)	0.84 (0.06)
	May 2001	5	9.5	0.55 (0.07)	1.73 (0.56)
	Aug. 2001	5	8.6	0.86 (0.14)	1.43 (0.24)
	Oct. 2001	5	8.1	0.98 (0.16)	1.09 (0.19)
	mean	23	8.8	0.64 (0.07)	1.07 (0.17)
Deerfield	Oct. 2000	5	5.6	0.55 (0.09)	0.80 (0.16)
	Feb. 2001	3	-	1.01 (0.51)	2.22 (0.56)
	May 2001	5	3	2.79 (0.20)	4.33 (1.04)
	Aug. 2001	5	5.2	2.39 (0.24)	2.35 (0.56)
	Oct. 2001	5	4.8	1.88 (0.16)	1.38 (0.28)
	mean	23	4.7	1.79 (0.20)	2.22 (0.37)
Sheridan	Oct. 2000	5	2.7	1.78 (0.39)	1.57 (0.42)
	Feb. 2001	3	-	no data	4.40(1.50)
	May 2001	5	2.7	4.82 (0.16)	3.40 (0.69)
	Aug. 2001	5	2.8	4.72 (0.19)	2.9 (0.87)
	Oct. 2001	5	4.5	5.08 (0.24)	2.78 (1.02)
	mean	23	3.1	4.10 (0.33)	2.67 (0.39)
Stockade	Oct. 2000	5	1.8	3.78 (0.23)	3.90 (0.31)
	Feb. 2001	3	-	1.14 (0.10)	0.67 (0.18)
	May 2001	5	3.7	3.25 (0.25)	2.78 (0.39)
	Aug. 2001	5	1.7	17.76(0.71)	13.12 (1.69)
	Oct. 2001	5	2.2	9.28 (0.75)	7.01 (0.69)
	mean	23	2.4	7.55 (1.29)	5.91 (0.98)

strongly correlated with total phosphorus concentration in Black Hills reservoirs (Figure 2), implying that phosphorus is the limiting nutrient to algal productivity.

Phosphorus concentrations varied appreciably among Black Hills reservoirs with mean values ranging from 12 µg/L in Pactola Reservoir to 81 µg/L in Stockade Reservoir (Table 2). Similarly, nitrate (NO_3^-) and ammonia (NH_4^+) concentrations were generally lowest in Pactola Reservoir and highest in Stockade Reservoir (Table 3). Summer hypolimnetic dissolved oxygen concentration was appreciably low in Deerfield, Sheridan and Stockade reservoirs (Figure 3) whereas hypolimnetic oxygen concentration in Pactola reservoir remained above 4 mg/L throughout the year. Reduction of summer hypolimnetic dissolved oxygen was associated with significant increases in total phosphorus concentration measured near the sediments in Deerfield, Sheridan and Stockade reservoirs (Figure 4). In Stockade Reservoir, for example, total phosphorus concentration near the sediments increased from 60 µg/L in May to over 140 µg/L in August 2001.

Using seasonal measurements of Secchi depth, chlorophyll *a* biomass and total phosphorus concentration, we calculated trophic state indices (TSI scores) for each reservoir (Table 4). TSI reflects the 'trophic state' of lakes and reservoirs where values < 30 are indicative of oligotrophy, 50 to 70 indicate eutrophic conditions and values >70 are often characteristic of hypereutrophic conditions (Carlson 1977). Based on chlorophyll *a* biomass, mean TSI scores were 25, 34, 48 and 46 for Pactola, Deerfield, Sheridan and Stockade reservoirs. Factors such as nutrient availability, zooplankton grazing, and nonalgal sources of turbidity can have an important influence on seasonal variation in TSI scores. To better understand factors affecting TSI scores, deviation of TSI relationships can be represented graphically as proposed by Carlson (1992). In the example plot depicted by Figure 5, values that fall above the x-axis imply increased P limitation. Points to the right of the y-axis indicate that water transparency is higher than that predicted by algal biomass, such as dominance by large cyanobacteria or increased zooplankton grazing and subsequent decreases in small particles (Wetzel 2001). Conversely, points to the left of the y-axis in the lower left diagonal indicate that water transparency is lower than predicted by algal biomass as a result of suspended sediment or small, non-algal

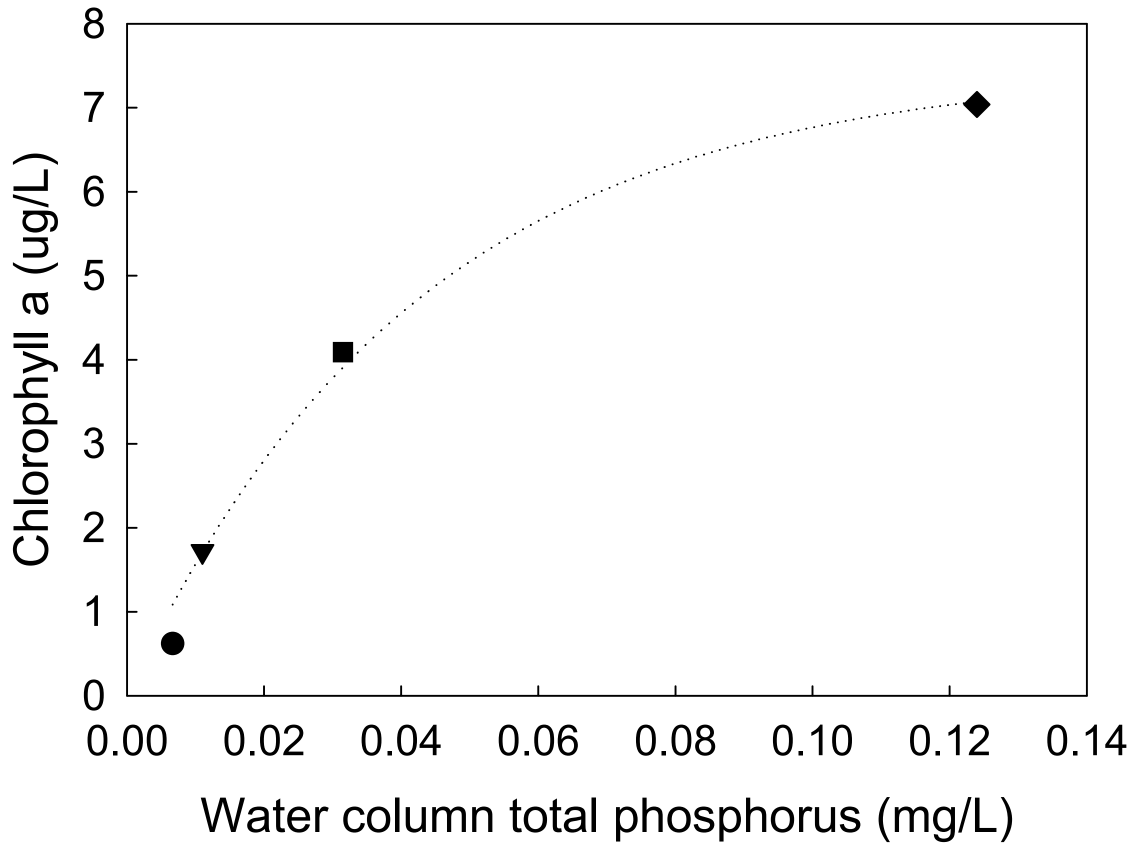

Figure 2. Relationship between mean algal biomass and mean surface phosphorus concentration for Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Regression line was fitted to the equation CHLa= 7.48(1-e-23.45TP) (r2= 0.99, P= 0.005).

Table 2. Mean total phosphorus (TP) concentration measured in Black Hills reservoirs from October 2000 to October 2001. Samples were taken 1 m below the surface and 1 m above the bottom. Values in parentheses represent 1 SE.

Reservoir	Sample date	n	Surface TP (mg/L)	Bottom TP (mg/L)
Pactola	Oct. 2000	5	0.012 (0.005)	0.024 (0.009)
	Feb. 2001	3	0.011 (0.005)	0.017 (0.002)
	May 2001	5	0.005 (0.002)	0.008 (0.001)
	Aug. 2001	5	0.007 (0.002)	0.011 (0.002)
	Oct. 2001	5	0.028 (0.009)	0.020 (0.003)
	mean	23	0.013 (0.003)	0.016 (0.002)
Deerfield	Oct. 2000	5	0.041 (0.014)	0.047 (0.018)
	Feb. 2001	3	0.025 (0.008)	0.023 (0.008)
	May 2001	5	0.012 (0.003)	0.012 (0.004)
	Aug. 2001	5	0.011 (0.004)	0.022 (0.003)
	Oct. 2001	5	0.033 (0.003)	0.052 (0.015)
	mean	23	0.024 (0.004)	0.032 (0.006)
Sheridan	Oct. 2000	5	0.035 (0.005)	0.010 (0.032)
	Feb. 2001	3	0.044(0.007)	0.026 (0.007)
	May 2001	5	0.022 (0.003)	0.025 (0.003)
	Aug. 2001	5	0.032 (0.002)	0.084 (0.019)
	Oct. 2001	5	0.032 (0.003)	0.140 (0.046)
	mean	23	0.0318 (0.002)	0.078 (0.015)
Stockade	Oct. 2000	5	0.094 (0.009)	0.105 (0.010)
	Feb. 2001	3	0.026 (0.006)	0.068 (0.033)
	May 2001	5	0.048 (0.004)	0.057 (0.006)
	Aug. 2001	5	0.124 (0.004)	0.144 (0.032)
	Oct. 2001	5	0.111 (0.004)	0.109 (0.003)
	mean	23	0.085 (0.008)	0.099 (0.010)

Table 3. Mean water quality values averaged from vertical profiles taken in Black Hills reservoirs from October 2000 to October 2001. Data were collected using a YSI DataSonde. See Appendix C for raw data summary.

Parameter	Unit	Pactola	Deerfield	Sheridan	Stockade
Temperature	°C	10.95	11.14	10.53	13.68
Dissolved oxygen	mg/L	8.96	6.24	4.63	5.56
pH	--	8.28	8.24	8.01	8.34
Specific conductance	μS/cm	363.3	385.4	304.5	312.3
Total dissolved solids	mg/L	0.236	0.251	0.198	0.203
Turbidity	NTU	1.05	2.30	2.68	2.52
ORP	mV	178.1	157.2	181.3	167.5
NO_3	mg/L	16.3	30.0	46.6	44.1
NH_3	mg/L	0.006	0.005	0.010	0.029
NH_4	mg/L	0.138	0.120	0.397	0.439

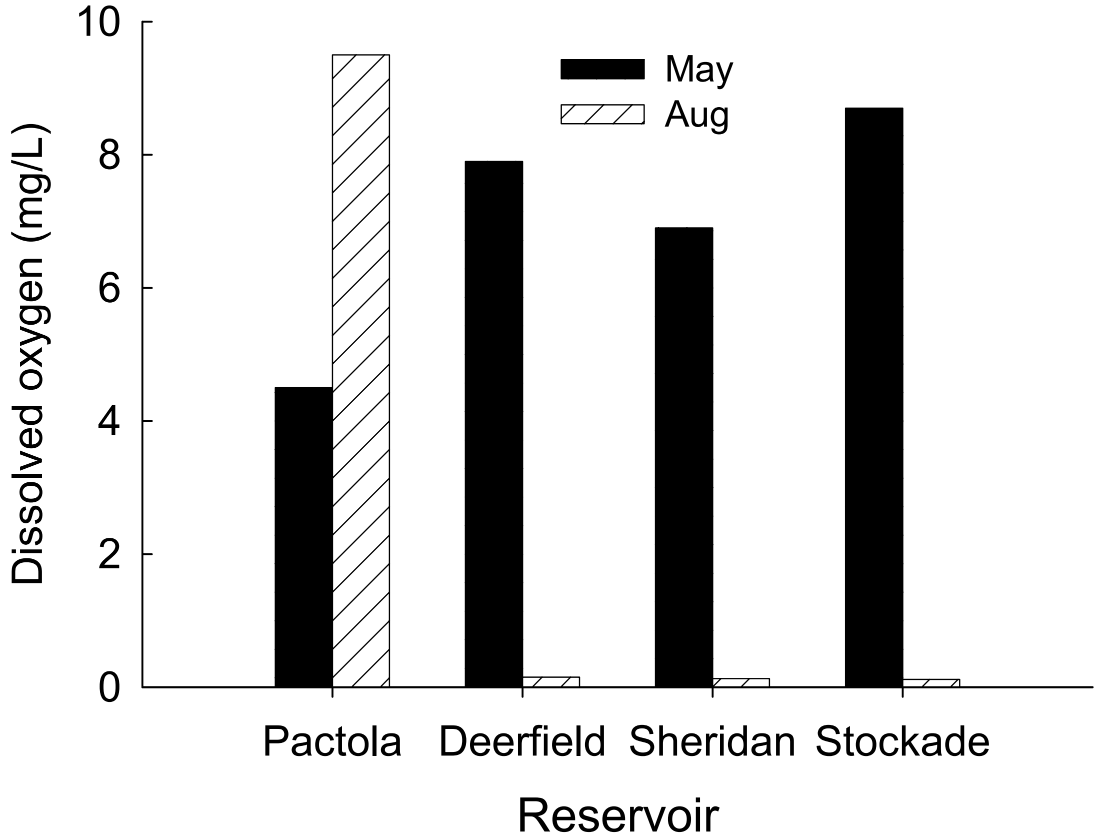

Figure 3. Dissolved oxygen concentration measured near the sediment-water interface in May and August 2001 in Pactola, Deerfield, Sheridan, and Stockade reservoirs.

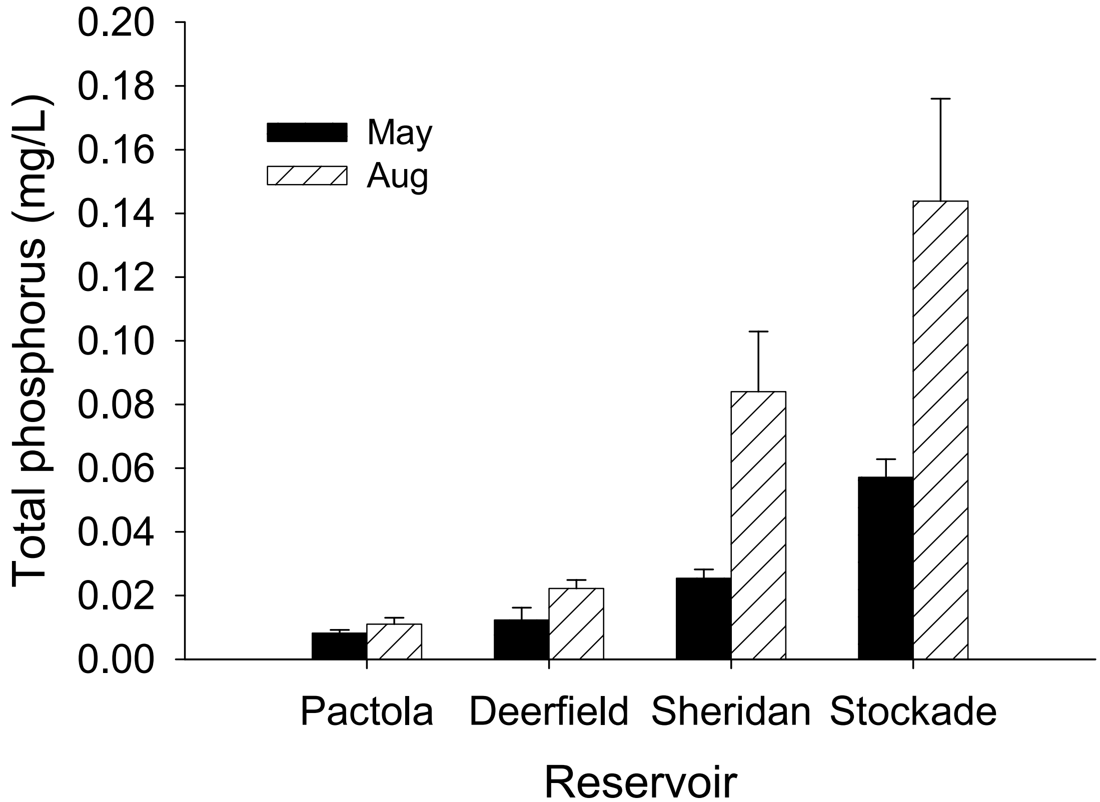

Figure 4. Total phosphorus concentration measured near the sediment-water interface in May and August 2001 in Pactola, Deerfield, Sheridan, and Stockade reservoirs. P values are given for each reservoir comparing total phosphorus concentration in May vs. August (Student's T-Test). Vertical bars represent 1 S.E.

Table 4. Seasonal Trophic State Index (TSI) values calculated from total phosphorus (TSI_{TP}), Secchi depth (TSI_{SD}), and chlorophyll a (TSI_{CHL}) in Pactola, Deerfield, Sheridan, and Stockade reservoirs.

Reservoir	Sample date	TSI_{TP}	TSI_{SD}	TSI_{CHL}
Pactola	Oct. 2000	40.50	28.26	19.98
	Feb. 2001	38.55	*	21.58
	May 2001	27.92	27.56	24.66
	Aug. 2001	31.54	28.99	29.07
	Oct. 2001	51.96	29.86	30.42
	mean	38.09	28.67	25.14
Deerfield	Oct. 2000	57.84	35.17	24.74
	Feb. 2001	50.57	*	30.74
	May 2001	40.50	44.17	40.68
	Aug. 2001	38.75	36.24	39.16
	Oct. 2001	54.38	37.40	36.82
	mean	48.41	38.25	34.43
Sheridan	Oct. 2000	55.51	45.96	36.23
	Feb. 2001	58.61	*	67.91
	May 2001	48.55	45.96	46.03
	Aug. 2001	53.90	45.42	45.82
	Oct. 2001	54.04	38.33	46.54
	mean	54.12	43.92	48.51
Stockade	Oct. 2000	69.62	51.53	43.63
	Feb. 2001	51.11	*	31.85
	May 2001	60.09	41.15	42.16
	Aug. 2001	73.65	52.35	58.82
	Oct. 2001	72.05	48.64	52.46
	mean	65.31	48.42	45.78

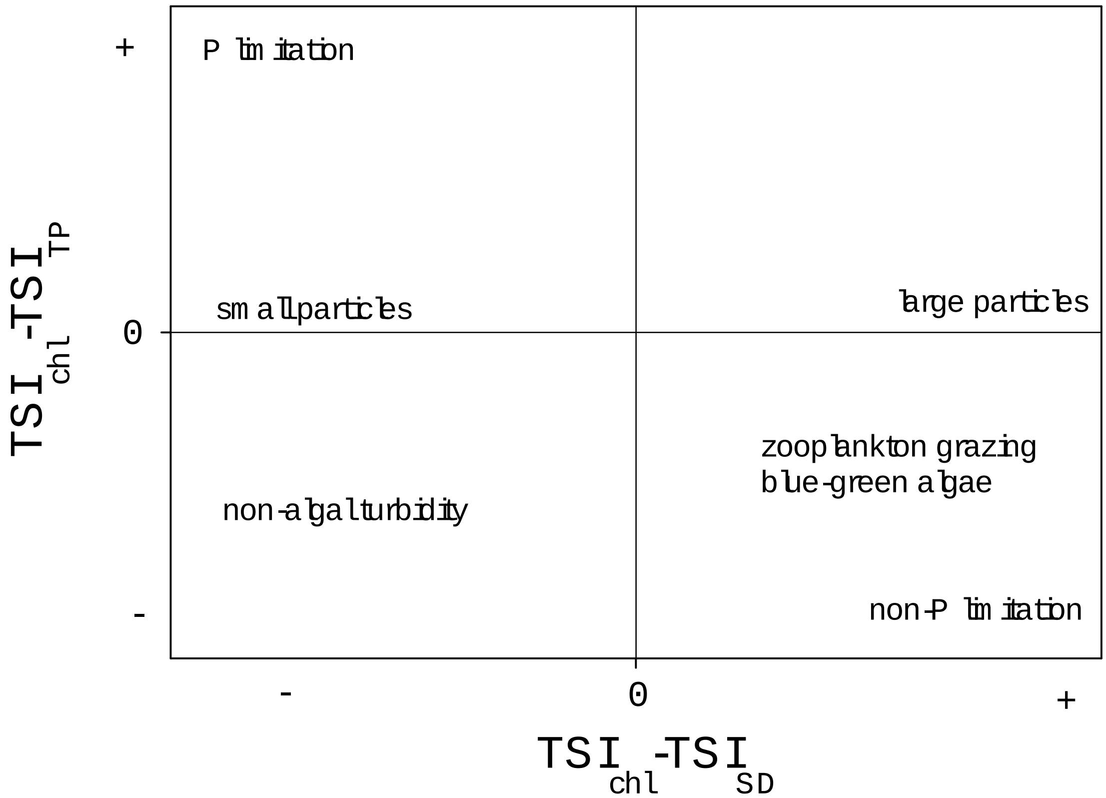

Figure 5. Potential factors that affect deviations in TSI relationships. Adopted from Carlson (1992).

particles. Patterns in seasonal TSI relationships were generally similar among Pactola, Deerfield and Sheridan reservoirs (Figure 6); in spring and summer months, water transparency in these reservoirs was reasonably well-predicted by algal biomass. However, in autumn months (October), factors other than phosphorus-limited algal biomass appear to influence water transparency in Black Hills reservoirs. In autumn 2000, for example, water transparency was generally lower than that predicted by algal biomass indicating that non-algal turbidity can affect water transparency in Black Hills reservoirs. In Stockade Reservoir, seasonal patterns in TSI scores reveal that factors other than phosphorus limitation may influence algal abundance and water transparency (Figure 6). In general, algal biomass was lower than predicted by total phosphorus concentration, indicating that zooplankton grazing, blue-green algae or, to a lesser extent, turbidity may influence seasonal TSI score.
In other reservoirs, we found little evidence that zooplankton grazing affected water transparency based on deviations in TSI scores.

External Phosphorus and Iron Inputs

Mean areal phosphorus inputs ranged from 0.53 mg P/m^2/d in Deerfield to 7.3 mg P/m^2/d in Stockade Reservoir (Table 5). Sheridan and Stockade reservoirs had appreciably higher external P loading rates than Pactola and Deerfield reservoirs (Table 5). The upper watersheds of Sheridan and Stockade reservoirs are characterized as some of the most developed in the Black Hills region (Black Hills Conservancy 1974), and may contribute to increased nutrient inputs from agricultural runoff, urbanization, etc.

Mean areal iron inputs varied appreciably among Black Hills reservoirs and ranged from 5.6 mg Fe/m^2/d in Deerfield to 132.4 mg Fe/m^2/d in Pactola Reservoir (Table 5). Areal iron inputs in Sheridan and Stockade reservoir averaged 67.9 and 120.5 mg Fe/m^2/d.

Reservoir phosphorus concentration was reasonably predicted from phosphorus loading rate (Figure 7). Comparison of observed and predicted values (i.e., percent difference) revealed that, on the average, the Dillon-Rigler model predicted reservoir nutrient levels within about 5%, although for individual reservoirs the percent

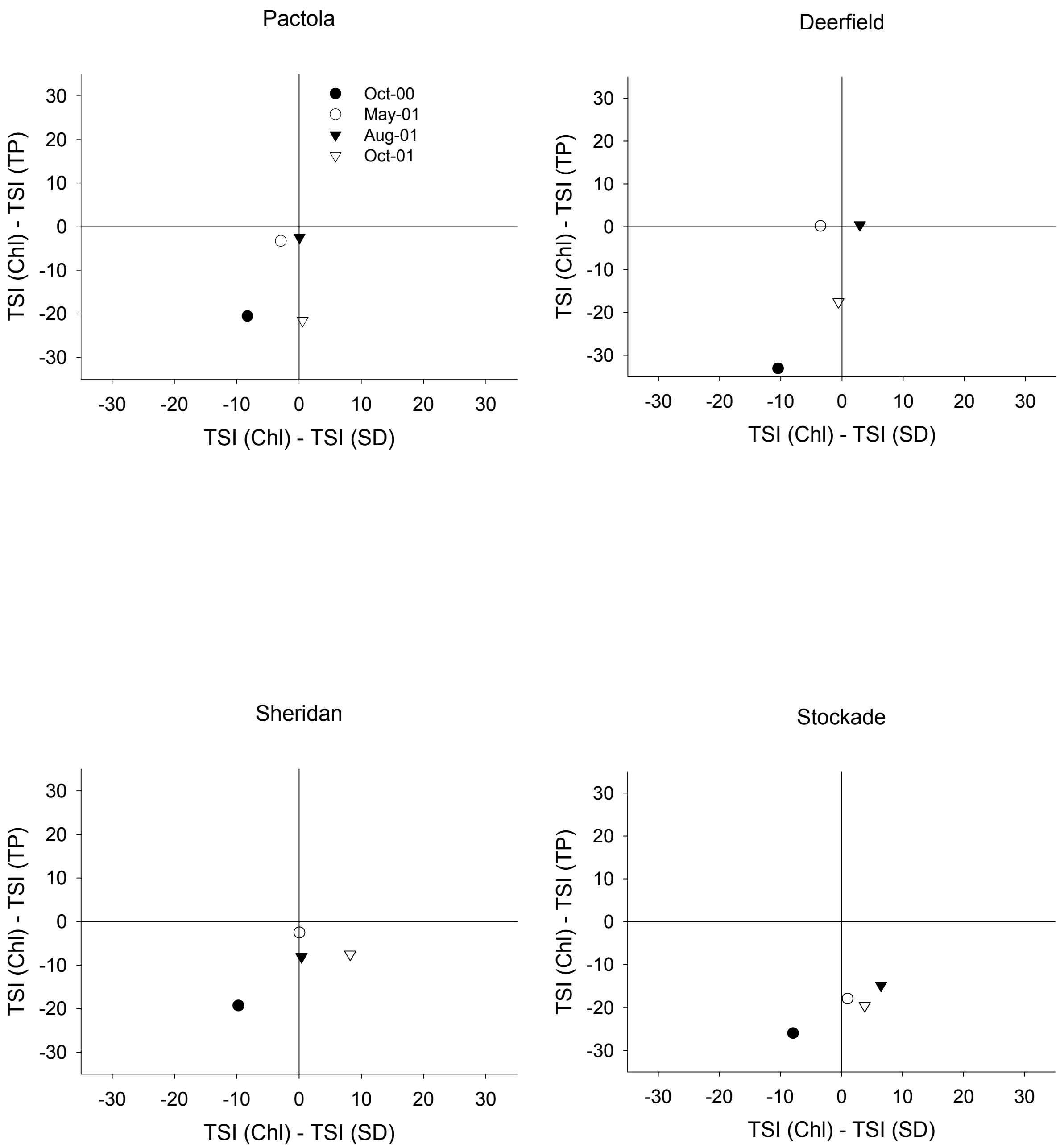

Figure 6. Seasonal deviations among TSI values for Pactola, Deerfield, Sheridan, and Stockade reservoirs.

Table 5. Mean tributary phosphorus (P) and iron (Fe) inputs measured from June 2001 through July 2001 for Pactola, Deerfield, Sheridan, and Stockade reservoirs. Values in parentheses represent 1 SE.

Reservoir	n	P Loading (mg P/m^2/d)	Fe Loading (mg Fe/m^2/d)
Pactola	8	1.31 (0.66)	132.40 (58.75)
Deerfield	8	0.53 (0.15)	5.55 (1.28)
Sheridan	8	4.78 (1.89)	67.89 (27.78)
Stockade	8	7.30 (4.56)	120.45 (85.03)

Table 6. Parameter values used to model phosphorus availability in Black Hills reservoirs. See text for details on the Dillon-Rigler model.

Reservoir	Areal annual P loading (mg P/m^2/y)[a]	Hydraulic residence time (y)	Mean depth (m)	Phosphorus retention (R)
Pactola	476.81	1.24	17.0	0.74
Deerfield	193.12	0.99	9.3	0.33
Sheridan	1745.90	0.56	9.0	0.73
Stockade	2664.51	0.22	4.8	0.41

[a] Note: Mass balance equation uses g P/m^2/y.

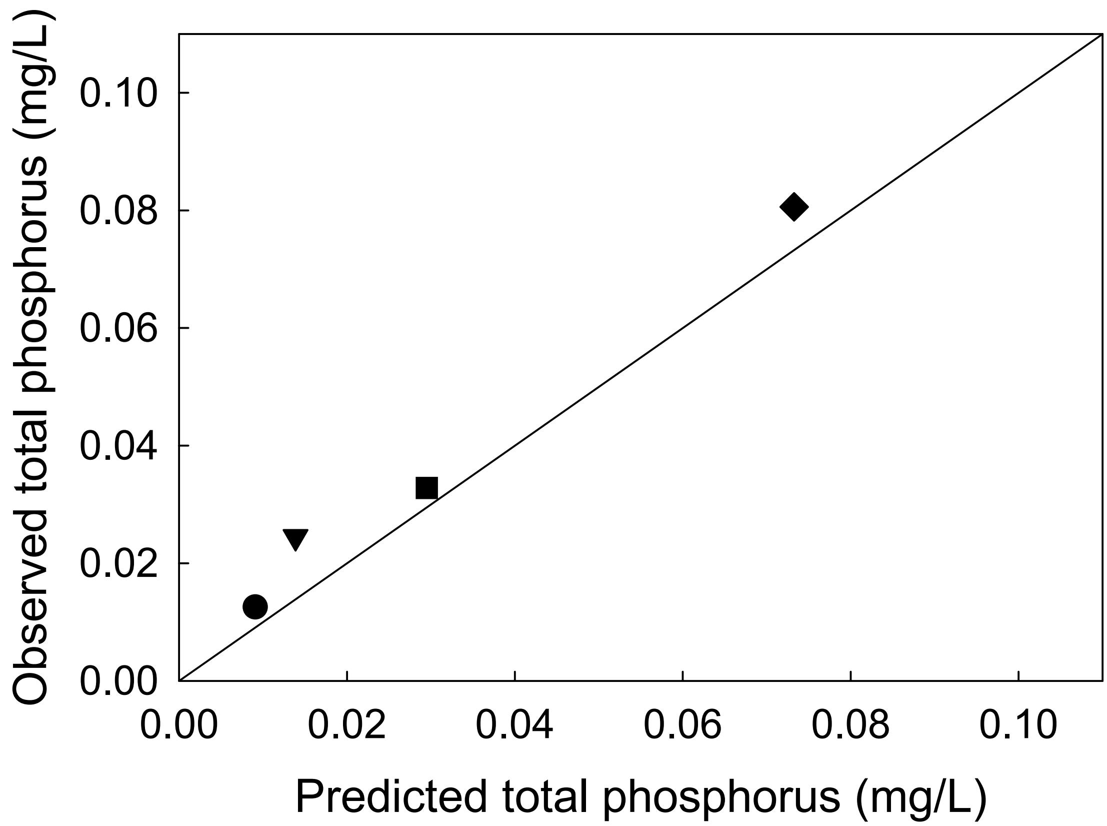

Figure 7. Comparison between observed and predicted total phosphorus concentration in Pactola, Deerfield, Sheridan, and Stockade reservoirs. Predicted phosphorus concentration was modeled using the Dillon-Rigler mass-balance model (see text for details). The diagonal line represents 1:1 correspondence between observed and predicted values.

difference between observed and predicted values was somewhat variable ranging from +6% in Sheridan to +50% in Deerfield Reservoir. Nonetheless, by combining information on P inputs, P retention and water residence time (Table 6), the Dillon-Rigler model should prove useful for modeling responses of reservoir nutrient levels to changes in external nutrient inputs.

Sediment Phosphorus and Iron Availability

Mean sediment phosphorus concentration differed significantly among reservoirs (ANOVA, df=3, F=7.79; P=0.003) and ranged from 0.7 mg P/g in Deerfield Reservoir to 1.8 mg P/g in Stockade Reservoir (Figure 8). Sediment P was significantly higher in Stockade Reservoir than in other Black Hills reservoirs. Pactola, the most oligotrophic reservoir in the Black Hills, had relatively high sediment phosphorus concentrations, second only to Stockade Reservoir. Bivariate plots of mean sediment P versus mean water column P, however, revealed that sediment phosphorus, by itself, was a poor predictor of reservoir nutrient concentration (correlation analysis, r=0.60, P=0.22; Figure 9).
Mean sediment iron concentration also varied among reservoirs (ANOVA, df=3, F=16.18, P<0.0001) and was significantly higher in Pactola reservoir than in other reservoirs (Figure 10). In general, sediment Fe concentrations in Black Hills reservoirs corresponded to areal Fe inputs (see Table 5). Because Pactola Reservoir had relatively high sediment Fe concentrations (Figure 10), the ratio of sediment P-to-Fe was appreciably lower in Pactola than in other Black Hills reservoirs (Figure 11). Moreover, mean phosphorus concentration in Black Hills reservoirs was positively related to sediment P:Fe ratio (Figure 12).

Using stepwise multiple regression analysis, we evaluated effects of 1) P:Fe ratio,2) sediment P, 3) sediment Fe, 4) dissolved oxygen concentration and 5) redox potential on phosphorus concentration near the sediment-water interface (i.e., bottom water samples). Although redox potential varied little with dissolved oxygen level (as expected) we used this as a potential explanatory variable because at very low oxygen levels (i.e., near anoxia), redox potential declines precipitously in Black Hills reservoirs (Figure 13). Based on a multiple regression model, sediment P, sediment Fe and redox potential explained about 80%

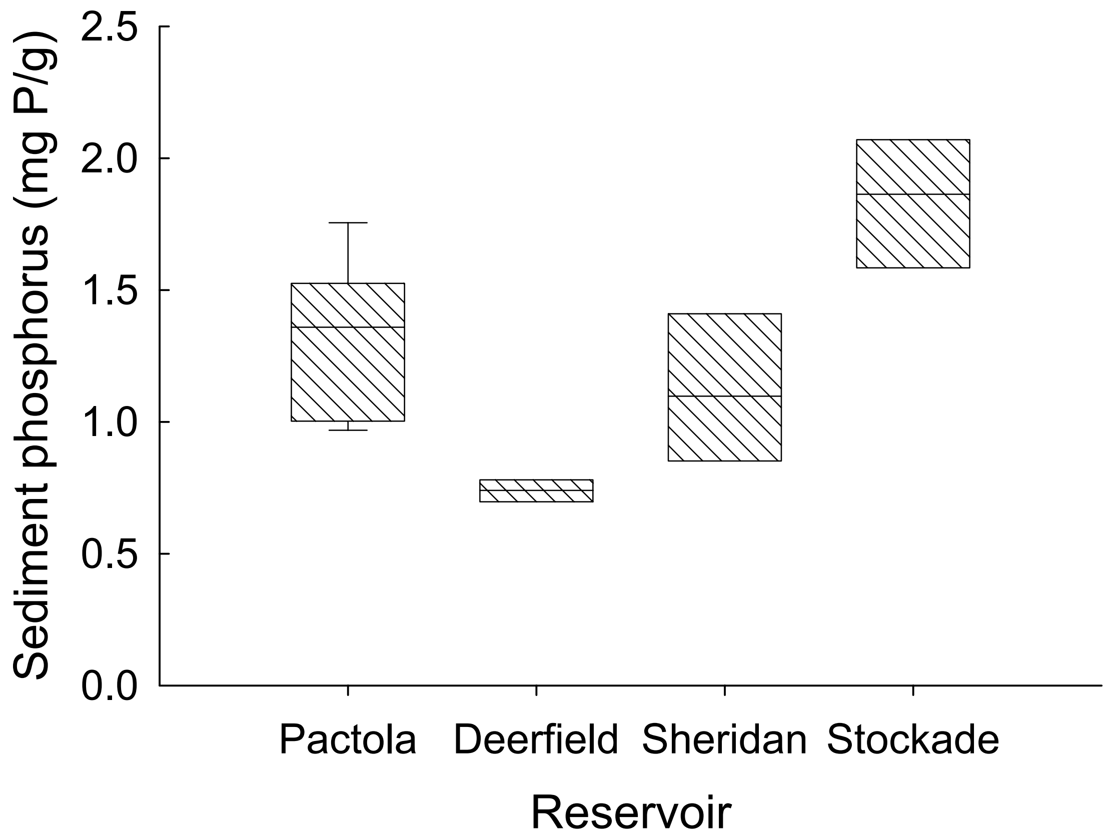

Figure 8. Sediment phosphorus values measured in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Horizontal bars in box plots represent medians; shaded area represents 25th and 75th percentiles and vertical bars represent 10th and 90th percentiles. Mean values with the same letter are not significantly different (Fisher's LSD, $P > 0.05$).

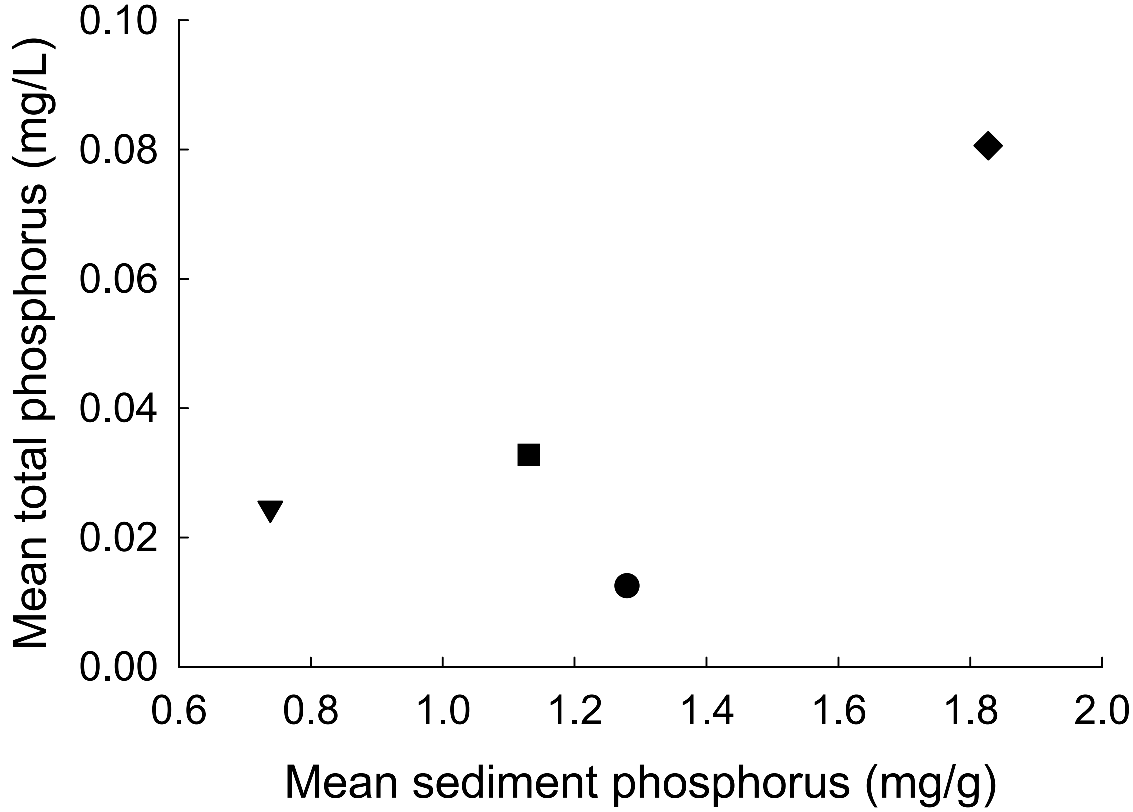

Figure 9. Mean water column phosphorus versus mean sediment phosphorus measured in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Relationship was not significant (correlation analysis, r=0.60, P= 0.22).

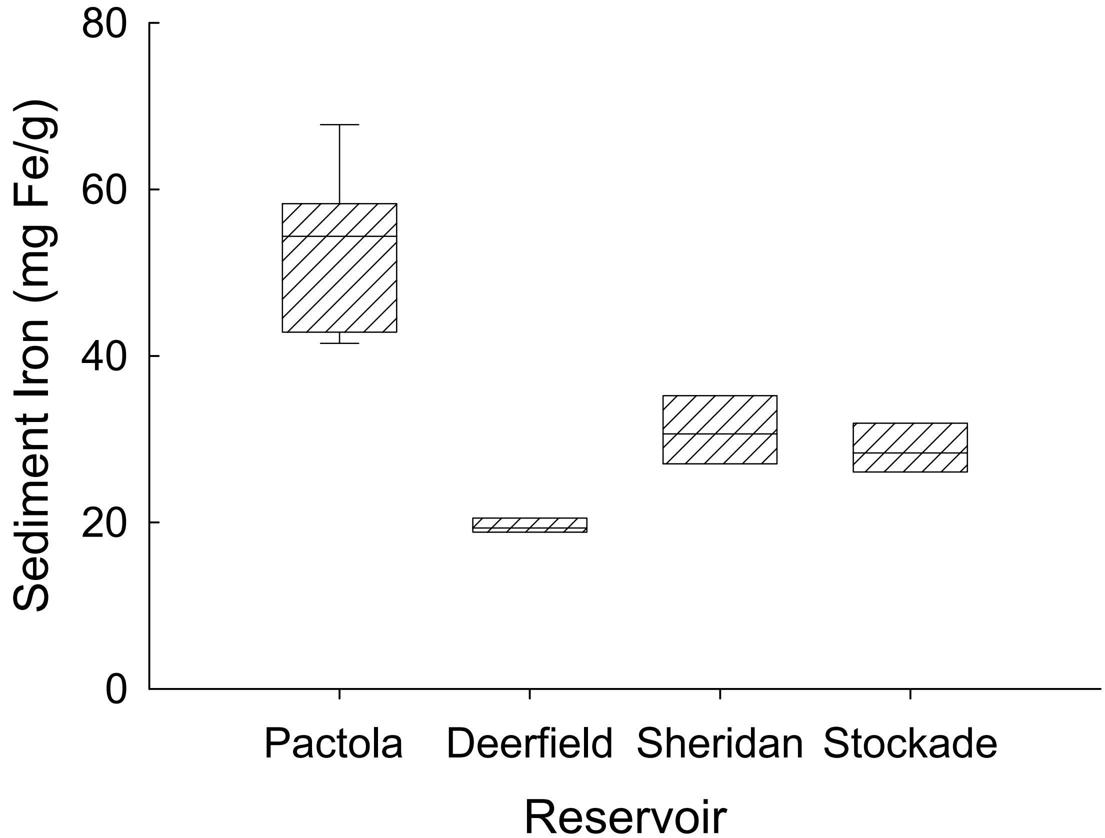

Figure 10. Sediment iron measurements in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Horizontal bars in box plots represent medians; shaded area represents 25th and 75th percentiles and vertical bars represent 10th and 90th percentiles. Mean values with the same letter are not significantly different (Fisher's LSD, P > 0.05).

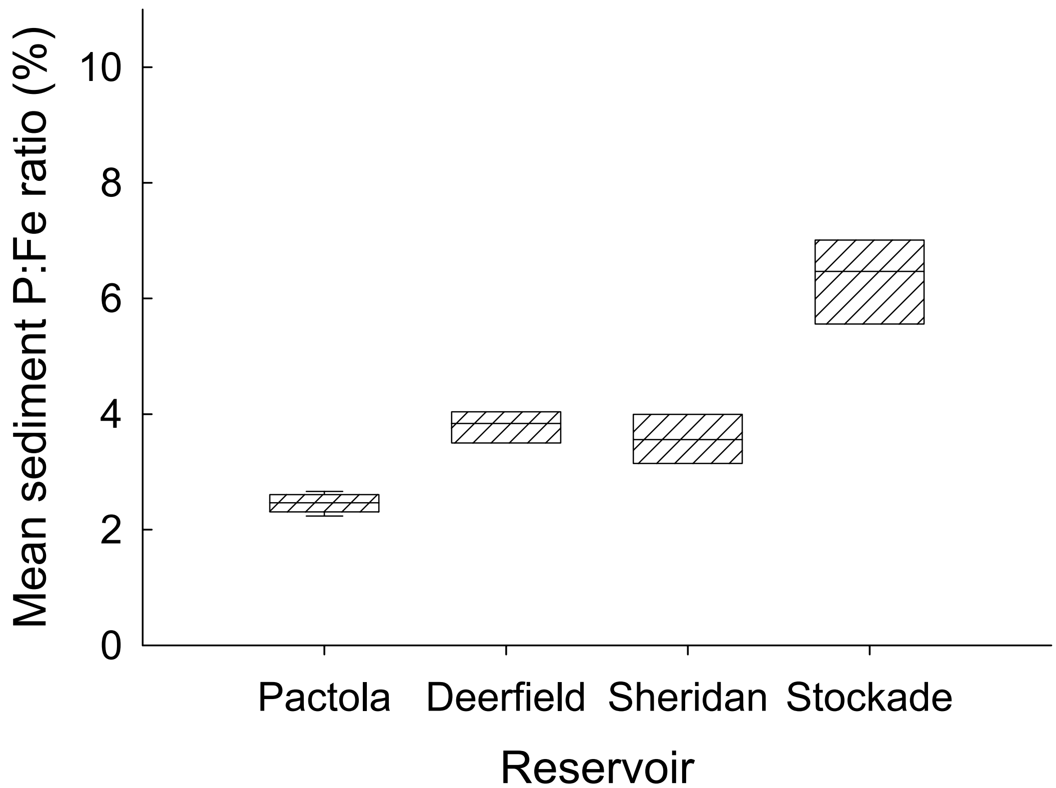

Figure 11. Sediment P:Fe ratios measured in Pactola, Deerfield, Sheridan, and Stockade reservoirs October 2000 to October 2001. Horizontal bars in box plots represent medians; shaded area represents 25th and 75th percentiles and vertical bars represent 10th and 90th percentiles. Mean values with the same letter are not significantly different (Fisher's LSD, $P > 0.05$).

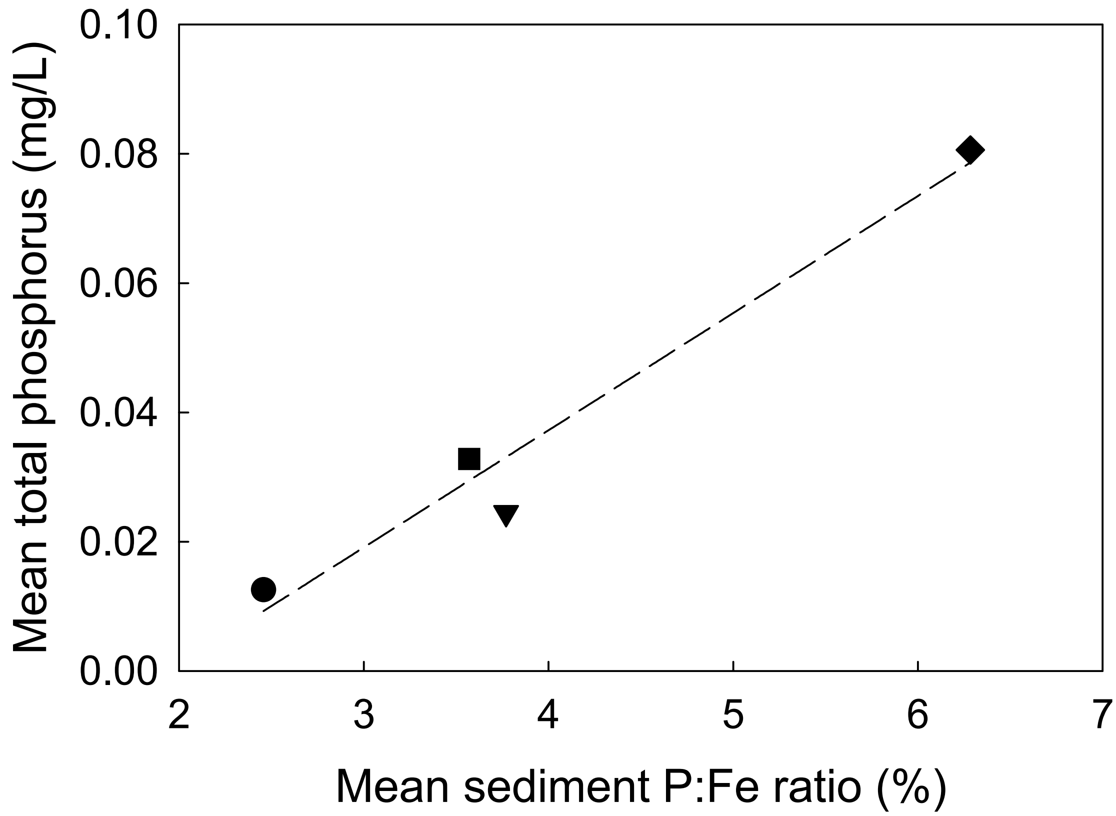

Figure 12. Relationship between mean water column phosphorus and mean sediment P:Fe ratio measured in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Total phosphorus (TP) can be predicted from P:Fe ratio as, TP= 0.181*(P:Fe) – 0.0353 (linear regression analysis; r2= 0.96, P= 0.02).

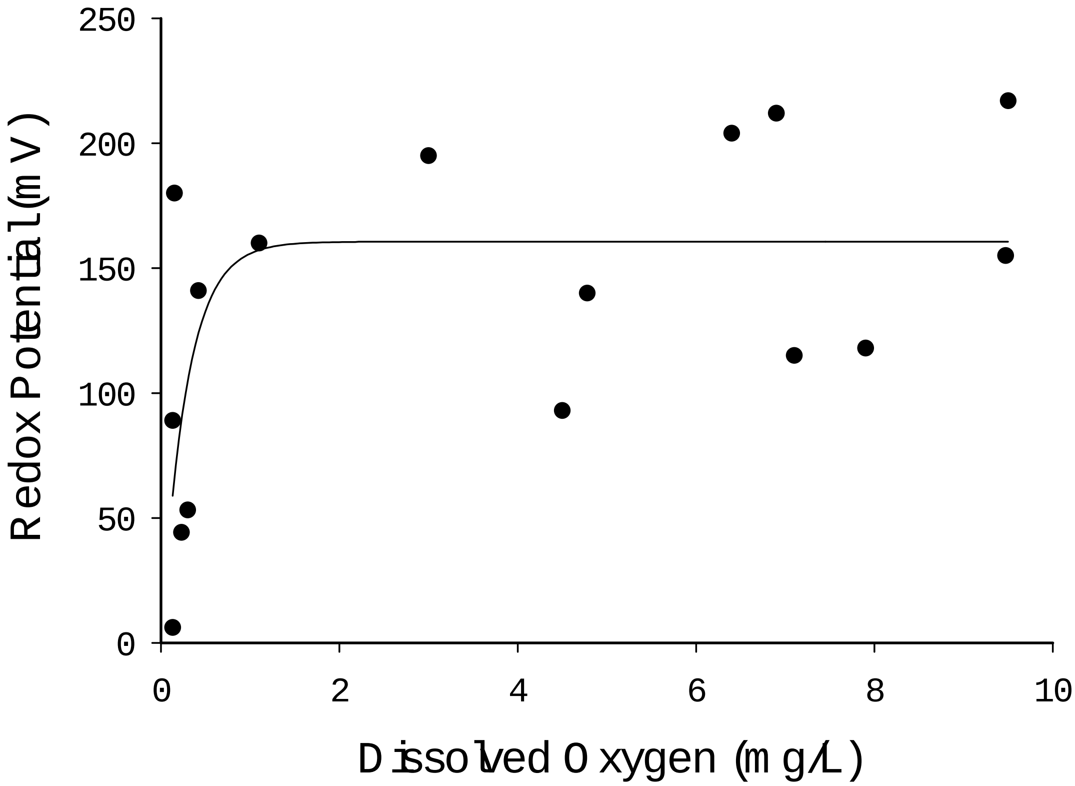

Figure 13. Relationship between redox potential and dissolved oxygen concentration in Black Hills reservoirs. The line was fitted using the equation, redox potential = 160.5(1-e-3.51*DO), r2=0.35, P=0.01.

of the variation in hypolimnetic phosphorus concentration (R^2=78%, P=0.0002). Because hypolimnetic phosphorus concentration was strongly correlated with phosphorus concentration in surface waters, this
model may be useful for evaluating changes in reservoir nutrient levels resulting from changes in sediment P, sediment Fe or redox condition (Figure 14). Questions regarding changes in hypolimnetic dissolved oxygen concentration (see Figure 13), for example, could be incorporated into the model to evaluate potential impacts on reservoir nutrient concentration (Figure 15).

Zooplankton Composition and Size Structure

Mean total zooplankton density was lowest in Pactola Reservoir (51.4/L) and highest in Stockade Reservoir (187.7/L; Figure 16). Total zooplankton abundance in Sheridan and Deerfield reservoirs was similar at 103.8/L and 112.0/L (ANOVA, Tukey's HSD, P = 0.97). Zooplankton biomass was a good indicator of reservoir productivity, as mean summer algal biomass was positively correlated with mean summer zooplankton biomass in Black Hills reservoirs (Figure 17).

Zooplankton abundance differed appreciably across reservoirs (Figures 18 and 19); copepods were a dominant component of the zooplankton community in Pactola and Deerfield reservoirs, comprising about 60 percent of total zooplankton biomass (Figure 20). Although species richness was similar across reservoirs (number of taxa=9), species composition varied (Table 7); the cladoceran community in Pactola and Deerfield reservoirs was dominated by *Daphnia galeata mendotae*, whereas in Sheridan and Stockade, *Daphnia pulex* was the dominant grazer (Figure 21). *Daphnia pulex* is typically larger and often out competes *Daphnia galeata mendotae* for abundant food resources (Prazakova 1991). However, planktivorous fishes generally prefer *Daphnia pulex* because of their larger body size (Brooks and Dodson 1965; Cerny and Bytel 1991). Lower food availability (algal biomass) combined with increased abundance of pelagic, planktivorous fishes (e.g., salmonids) in Pactola and Deerfield reservoirs, may favor *D. galeata* over *D. pulex*, although this hypothesis is not definitive given a lack of information on zooplankton selectivity and consumption rates by reservoir fishes.

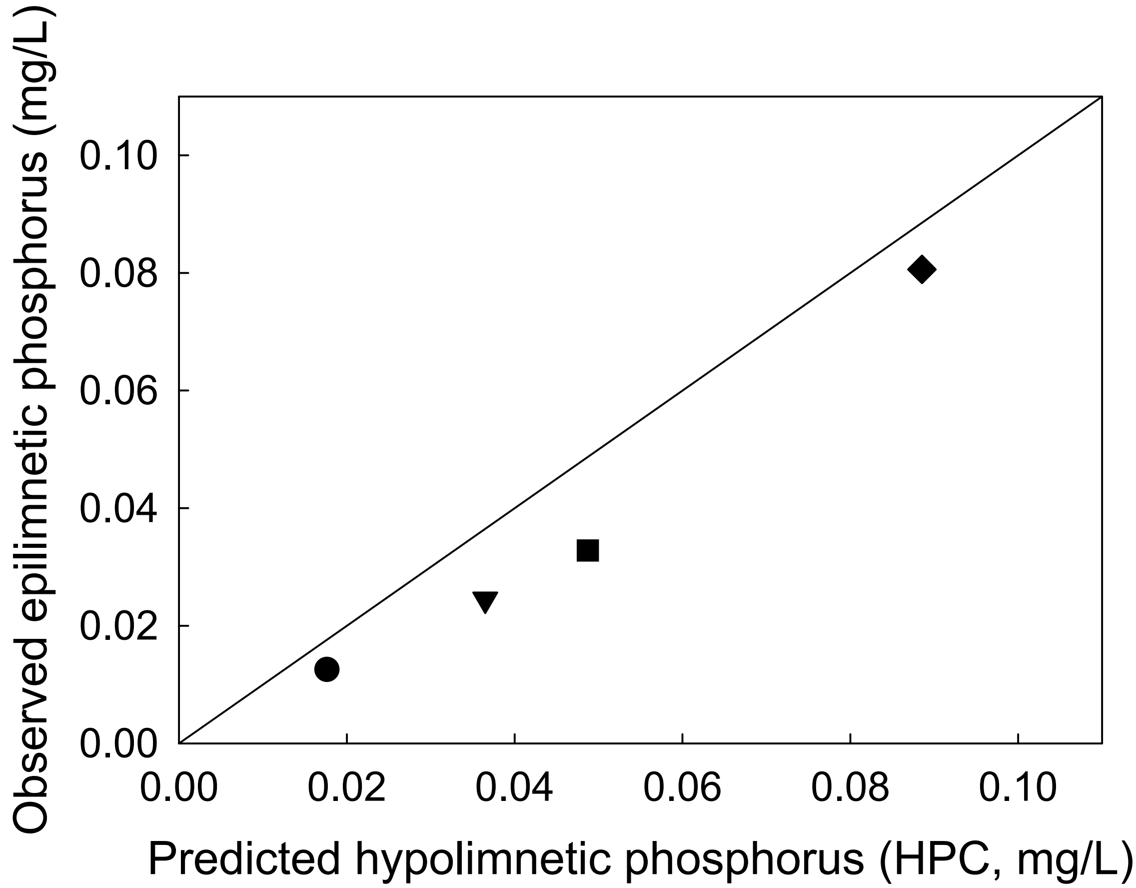

Figure 14. Relationship between epilimnetic phosphorus concentration and predicted hypolimnetic phosphorus concentration in Pactola, Deerfield, Sheridan, and Stockade reservoirs. Hypolimnetic phosphorus concentration (HPC) was predicted as, HPC = 0.0584 + 0.0633(sediment P) – 0.0013(sediment Fe) – 0.00034(ORP); multiple regression analysis, R2=0.78, P=0.0002. The diagonal line represents 1:1 correspondence.

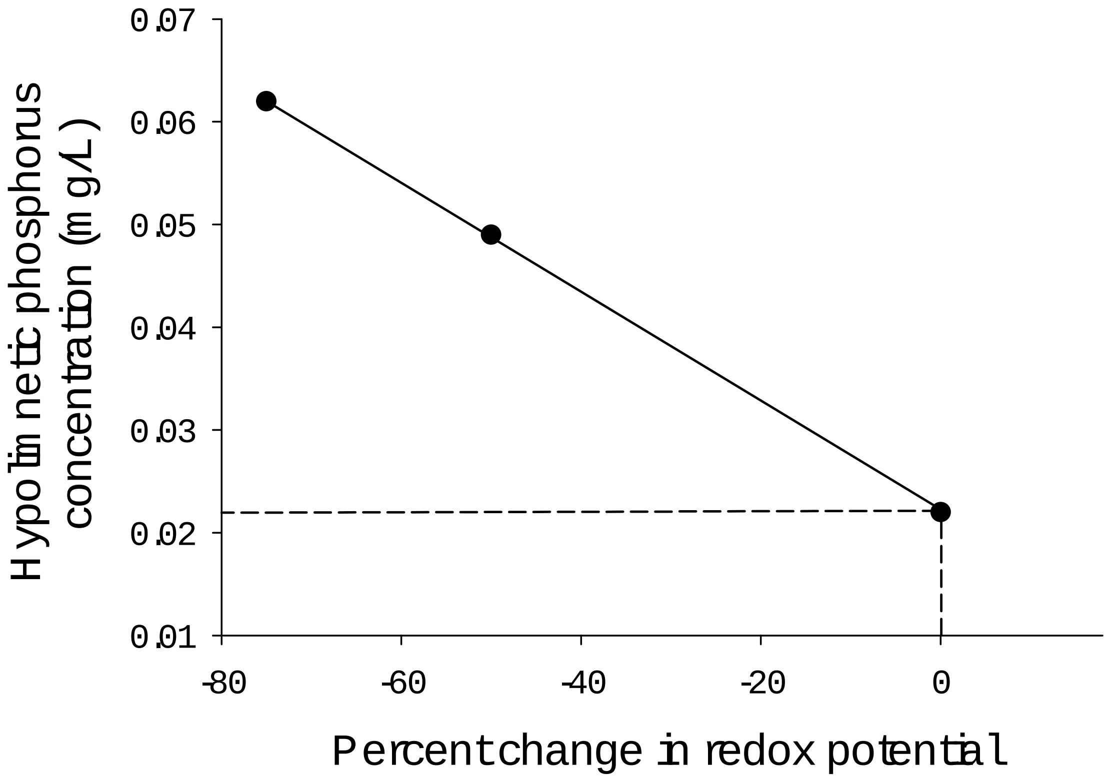

Figure 15. Model simulations showing effects of reduced redox potential on hypolimnetic phosphorus concentration for Pactola Reservoir. Dotted line represents observed condition (i.e., no change). Hypolimnetic phosphorus concentration was predicted from the equation given in Figure 14. Sediment phosphorus (1.4 mg/g) and sediment iron (55 mg/g) were held constant, and redox potential (155 mV) was reduced by 50 and 75%.

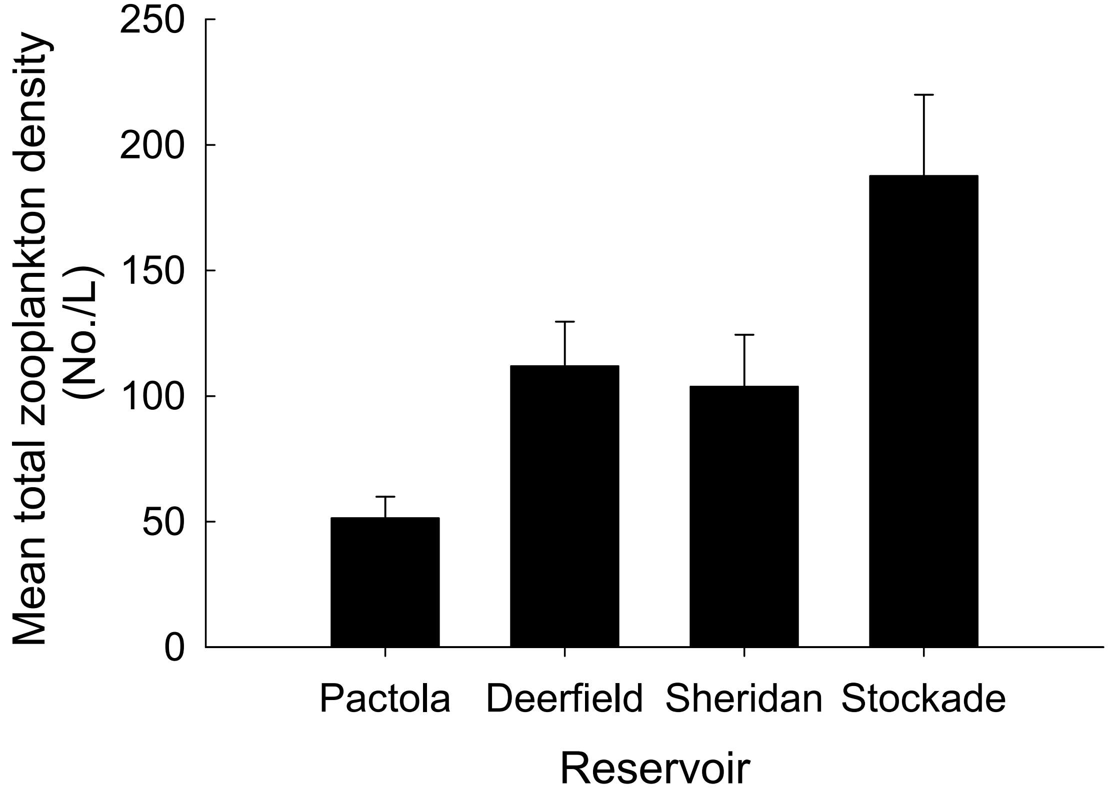

Figure 16. Mean total zooplankton abundance for Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. Means with the same letter are not significantly different (Tukey's multiple comparison test, P > 0.05). Vertical bars represent 1 S.E.

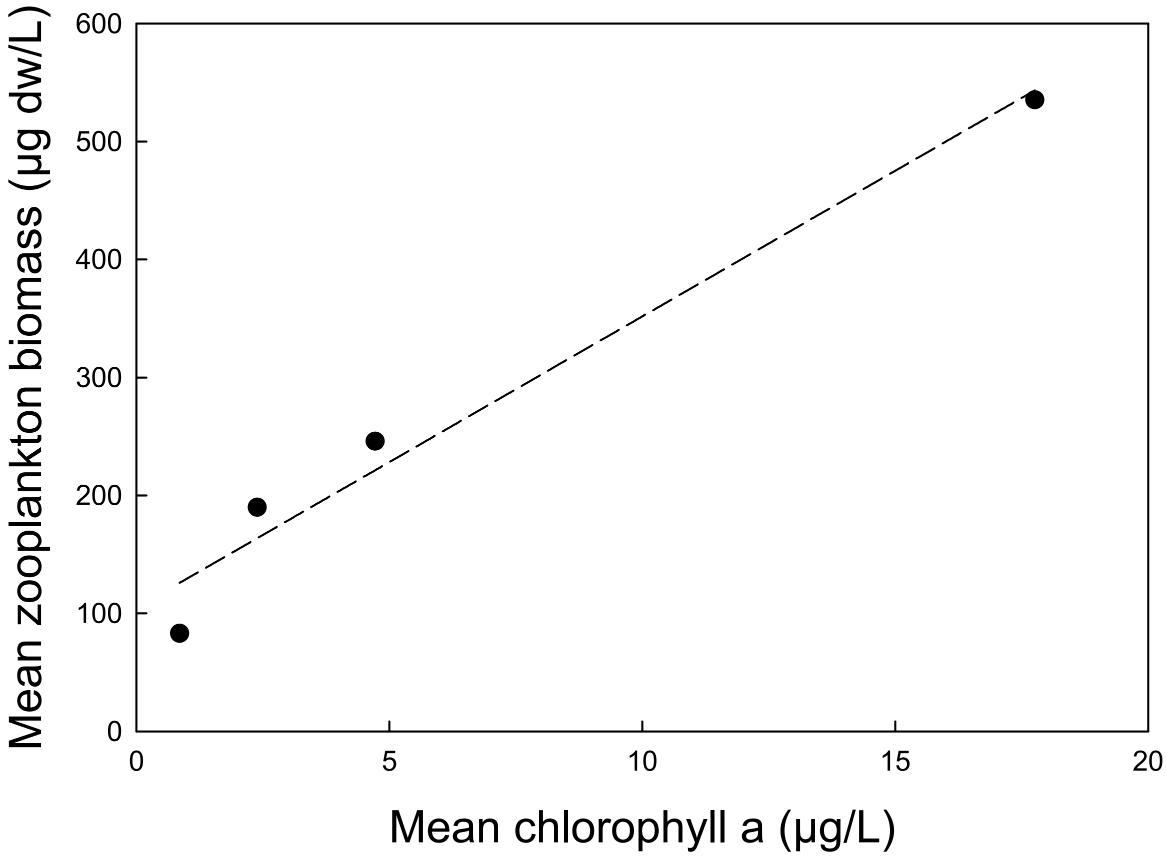

Figure 17. Relationship between mean total zooplankton biomass and mean algal biomass in Black Hills reservoirs. Values represent data collected in August 2001. Pearson's correlation coefficient and corresponding P-value are given.

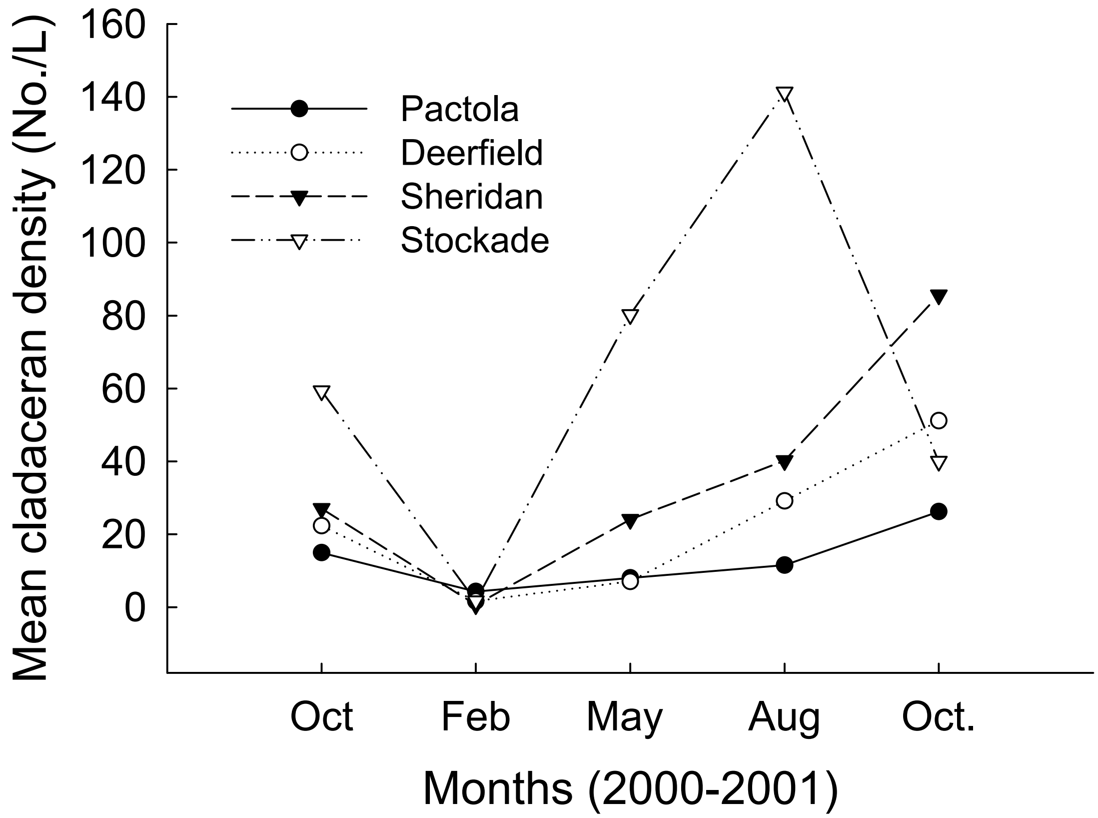

Figure 18. Seasonal cladoceran density in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001.

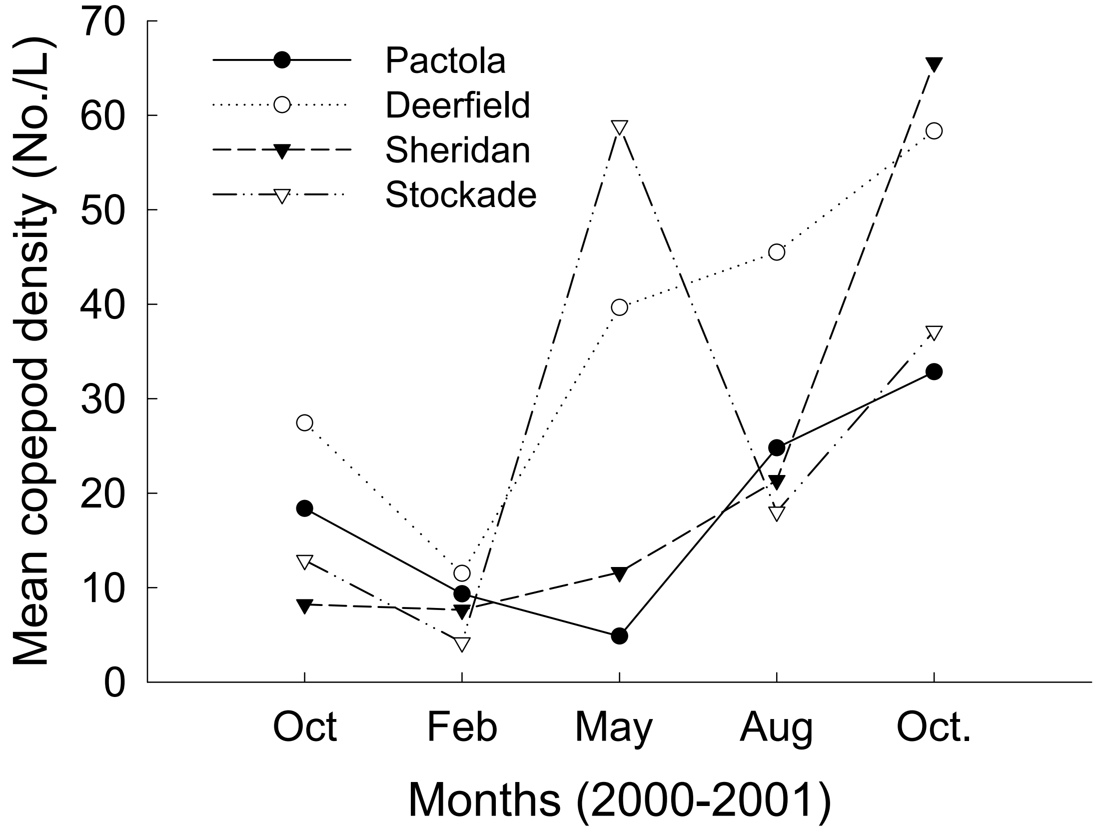

Figure 19. Seasonal copepod density in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001.

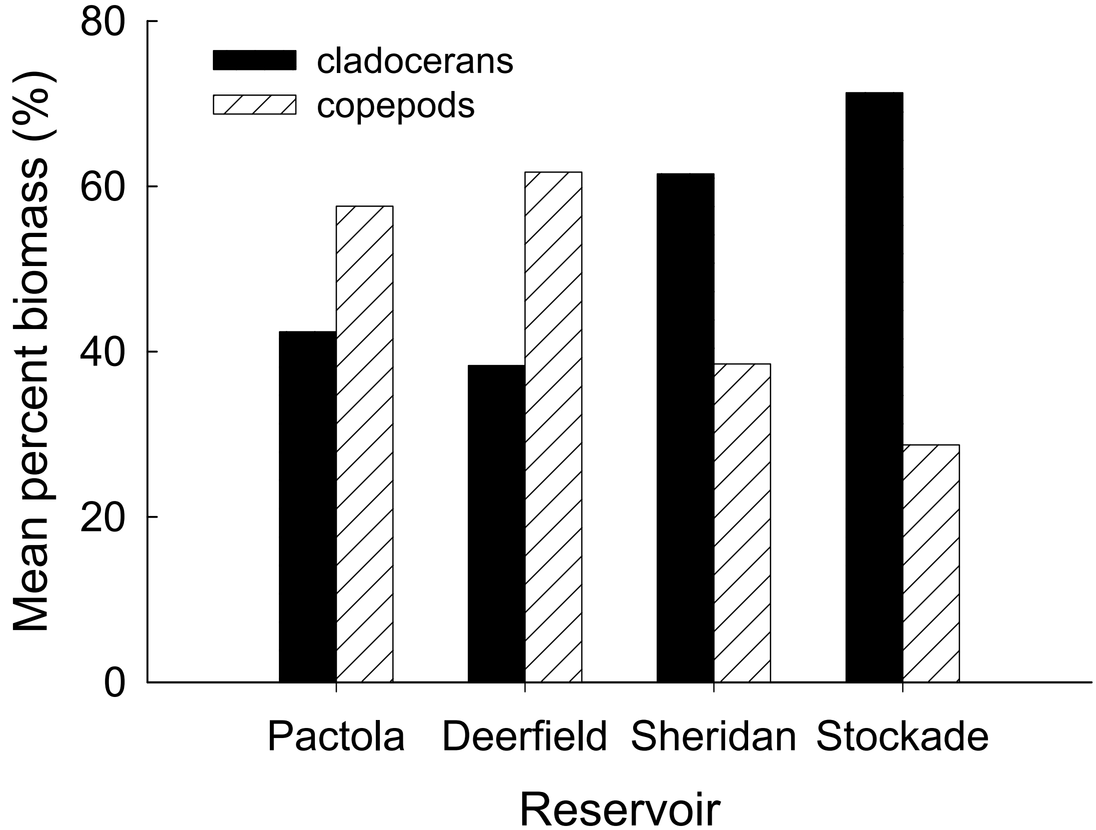

Figure 20. Mean percent cladoceran and copepod biomass in Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001. For each taxa (i.e., cladaceran or copepods), values with the same letter are not significantly different (Tukey's multiple comparison test, P > 0.05).

Table 7. Summary of zooplankton species composition in Pactola, Deerfield, Sheridan, and Stockade reservoirs (October 2000 to October 2001). 'X'= present, '---' = absent.

Species	Pactola	Deerfield	Sheridan	Stockade
Daphnia g. mendotae	X	X	X	X
Daphnia pulex	X	---	X	X
Ceriodaphnia lacustris	X	X	X	X
Alona costata	X	X	X	X
Camtocercus macrurus	---	X	---	---
Bosmina longirostris	X	X	X	X
Chydorus sphaericus	X	X	X	X
Diaptomus siciloides	X	X	X	X
Cyclops bicuspidatus	X	X	X	X

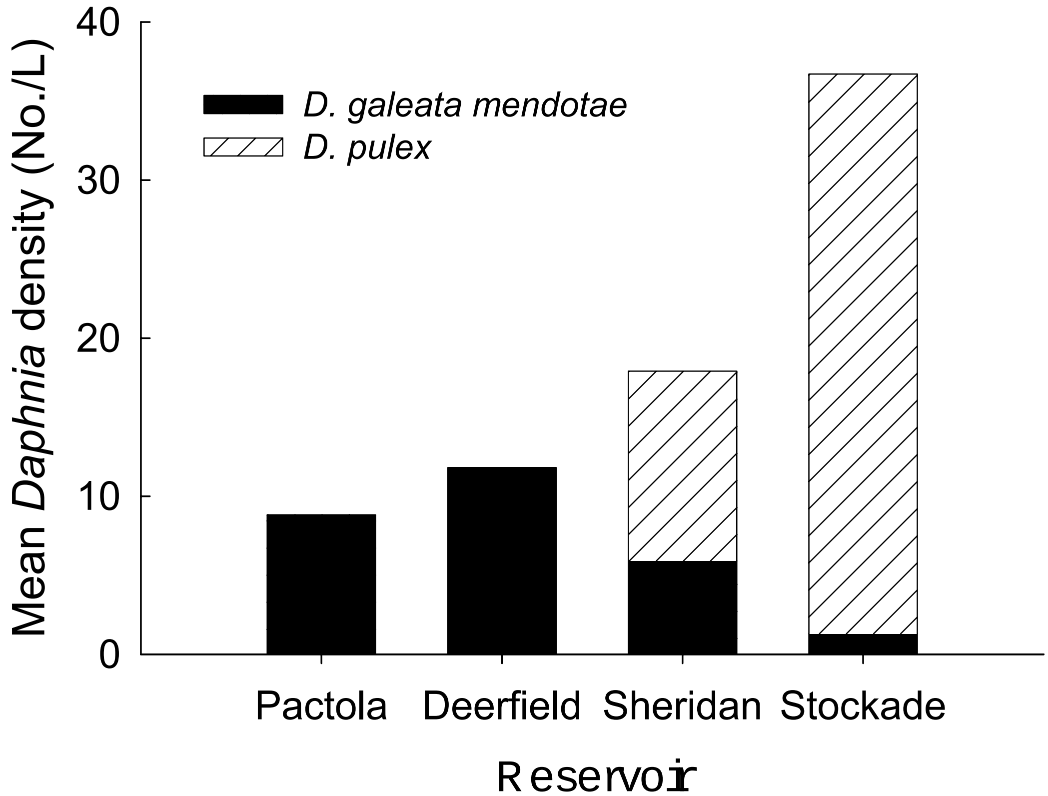

Figure 21. Mean annual abundance of D. galeata mendotae and D. pulex for Pactola, Deerfield, Sheridan, and Stockade reservoirs from October 2000 to October 2001.

CONCLUSION & RECOMMENDATIONS

Mechanisms regulating sediment phosphorus release have important implications for reservoir productivity. The potential for anoxic conditions was most pronounced following summer thermal stratification (i.e., August) in Deerfield, Sheridan, and Stockade reservoirs. By altering redox potential near the sediment-water interface, hypolimnetic anoxia can contribute to increased sediment P release. In contrast, the hypolimnion of Pactola Reservoir remains well oxygenated throughout the year providing an effective ‘barrier’ to sediment phosphorus release. The observation that sediment phosphorus levels were relatively high in Pactola Reservoir illustrates the importance of aerobic conditions as a buffer to sediment phosphorus release. Sediment phosphorus storage, however, could have important implications for future reservoir productivity. If the hypolimnion of Pactola Reservoir was to become anoxic in summer months, it is likely that internal phosphorus loading would contribute to increased phosphorus availability in the reservoir (see Figure 15).

The models evaluated here should prove useful for future water quality monitoring in Black Hills reservoirs. Dissolved oxygen concentration, redox potential, and phosphorus concentration are routinely collected by State and/or Federal agencies and can be used to assess (i.e., predict) potential changes in reservoir nutrient concentrations affecting productivity of Black Hills reservoirs.

REFERENCES

Black Hills Conservancy Sub-District, 1974. Water quality management plan for the Black Hills region. Publication #7, Appendix A Lake Management Data.

Bostrom, B., M. Jansson, and C. Forsberg. 1982. Phosphorus release from lake sediments. Arch. Hydrobiol. Beih. Ergebn. Limnol. 18: 5-59.

Brooks, J.L. and S.I. Dodson. 1965. Predation, body size, and composition of zooplankton. Science. 150: 28-35.

Carlson, R. E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22: 361-369.

Carlson, R. E. 1992. Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs. In Proceedings of a National Conference on Enhancing the States' Lake Management Programs. Monitoring and Lake Impact Assessment. Chicago. Pp. 59-71.

Carpenter, S.R., J.F. Kitchell, and J.R. Hodgson. 1985. Cascading trophic interactions and lake productivity. Bioscience 35: 634-639.

Cerny, M. and J. Bytel. 1991. Density and size distribution of *Daphnia* populations at different fish predation levels. Hydrobiologia. 225: 199-208.

Dillon, P.J. and F. H. Rigler. 1974. A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. Journal Fish. Res. Board of Canada. 31: 1771-1778.

Dumont, H.J., I. Van de Velde, S. Dumont. 1975. The dry weight estimate of biomass in a selection of Cladocera, Copepoda and Rotifera from the plankton, periphyton and benthos of continental waters. Oecologia 19: 75-97.

German, D. R. 1997. South Dakota Lake Protection Water Quality Report. Water Resources Institute, South Dakota State University. 30 pp.

Jensen, J. P., Kristensen, P., Jeppesen, E. and Skytthe, A. 1992. Iron phosphorus ratio in surface sediment as an indicator of phosphate release from aerobic sediments in shallow lakes. Hydrobiologia 235-236:731-743.

Mueller, D. 1982. Mass balance model estimation of phosphorus concentrations in reservoirs. Water Resources Bulletin 18: 377-382.

Pennak, R.W. 1989. Freshwater invertebrates of the United States, 3rd Edition. John Wiley and Sons, New York, NY.

Prazakova, M. 1991. Impact of fishery management on Cladoceran populations. Hydrobiologia 225: 209-216.

SAS Institute Inc., SAS® Procedures Guide, Version 8, Cary, NC; SAS Institute Inc., 1999.

Scheffer, M. 1998. Ecology of Shallow Lakes. Chapman & Hall. New York. 357 pp.

Sondergaard, M., P. Kristensen, and E. Jeppesen. 1993. Eight years of internal phosphorus loading and changes in the sediment phosphorus profile of Lake Sobygaard, Denmark. Hydrobiologia 253: 345-356.

Van der Molen, D. and P. C. M. Boers. 1994. The influence of internal loading on phosphorus concentration in shallow lakes before and after reduction of the external loading. Hydrobiologia 275/276: 379-389.

Wetzel, R. G. 2001. Limnology, 3rd Edition. Acad