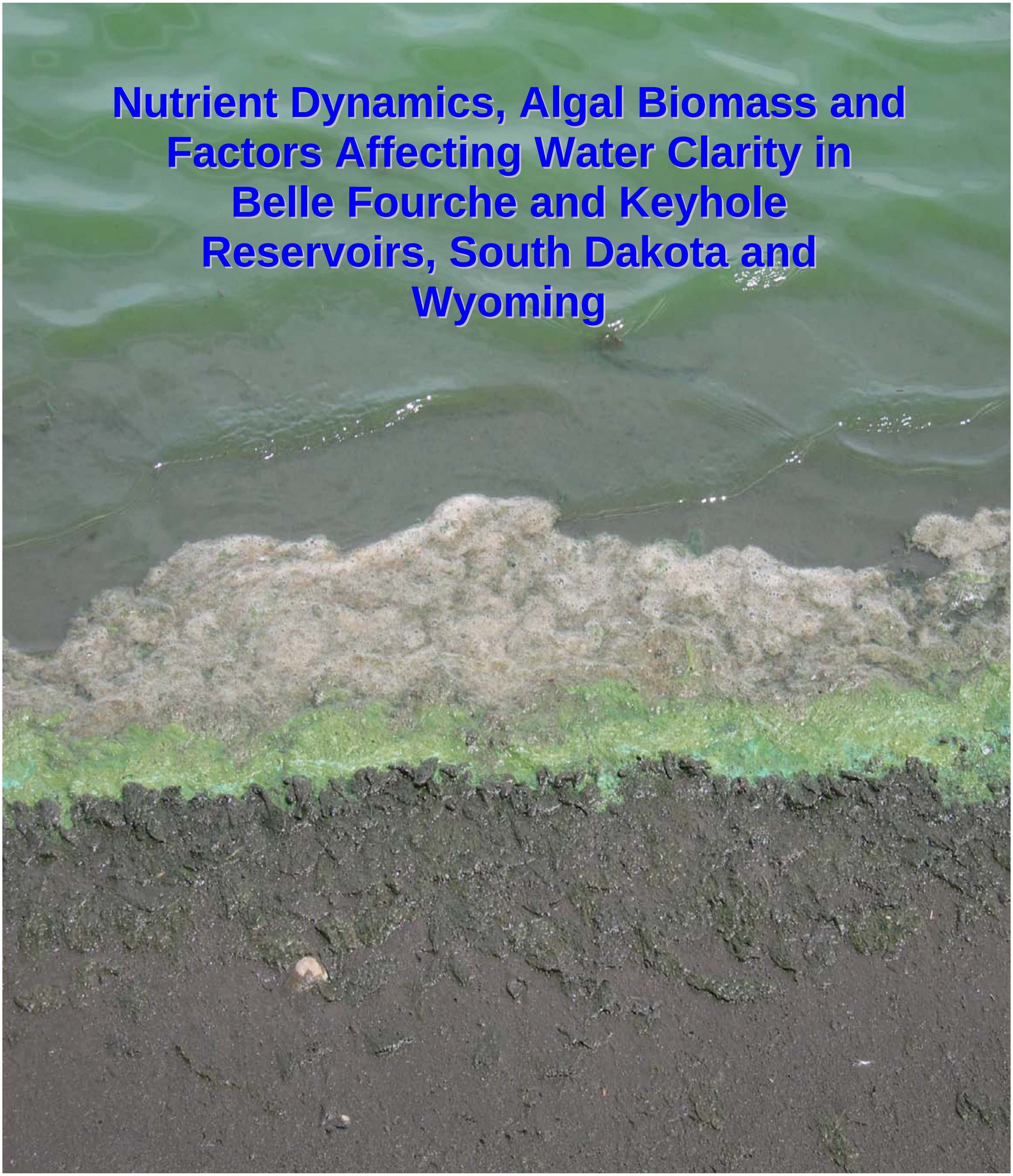
Nutrient Dynamics, Algal Biomass and Factors Affecting Water Clarity in Belle Fourche and Keyhole Reservoirs, South Dakota and Wyoming



ACKNOWLEDGEMENTS

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Cover: South shore of Belle Fourche Reservoir, September 2007

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Introduction

Belle Fourche and Keyhole reservoirs are located in the Belle Fourche River basin, South Dakota-Wyoming. Both reservoirs are operated by the U.S. Bureau of Reclamation and represent significant water resources to the region. Recreational use within Belle Fourche and Keyhole units has increased in recent years (DOI 2002; 2004). To meet these demands, resource management plans (RMP) have been completed that address several needs related to overall management of the units (DOI 2002; 2004). The purpose of the RMPs is to foster stewardship of public lands within the units. As changes in land management and recreation development occur, baseline data on water quality are needed. Keyhole Reservoir, for example, is currently listed as impaired for contact recreation due to periodic fecal coliform contamination. Moreover, upstream water use associated with coal bed methane extraction could potentially affect water quality (e.g., salinity) in the Belle Fourche River basin. This report documents baseline water quality characteristics in Keyhole and Bell Fourche reservoirs measured from May-October 2007.

Nutrient dynamics, turbidity, and zooplankton composition

Nutrient Dynamics

Phosphorus

Phosphorous has received considerable attention as a limiting nutrient in aquatic ecosystems. Because phosphorus occurs in a variety of forms, it can be difficult to determine the amount actually available for algae (Scheffer 1998). In practice, soluble reactive phosphorus (SRP) typically gives the best estimate of available phosphorus for algal growth, although total phosphorus is the most frequently reported value. The relationship between average phosphorus concentration in a lake (P) and average phosphorus concentration in inflowing water (P_i) can be expressed as a mass balance equation,

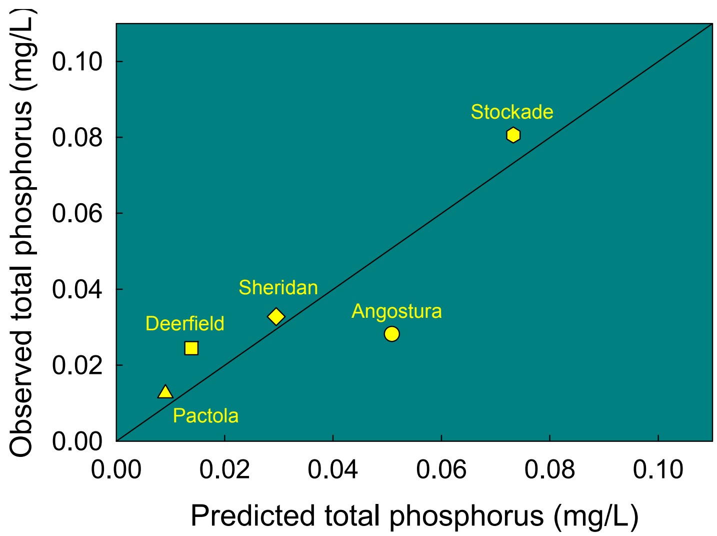

Fig. 1. Relationship between observed and predicted total phosphorus concentration in Black Hills reservoirs, South Dakota. Predicted phosphorus concentration was estimated using the Dillon-Rigler mass balance model. Solid line represents 1:1 correspondence.

$$P = (t_p / t_w)\, P_i \qquad (1)$$

where t_p is the average residence time of phosphorus and t_w is the average residence time of water. In principle, mass-balance equations can be used to predict effects of nutrient loading on phosphorus concentration in lakes and reservoirs. Using a similar approach, we observed strong correlations between annual average phosphorus concentrations and phosphorus concentration predicted by mass-balance equations for Black Hills reservoirs (Fig. 1).

Reducing external phosphorus loading is often a primary goal in preventing or reversing eutrophication in lakes and reservoirs. Often times, however, reductions in external loading have little effect on productivity of receiving waters. The reason for this centers on the importance of sediment as a phosphorus buffer and an understanding of the mechanisms that govern sediment phosphorus release. Several factors can influence the release of phosphorus from reservoir sediments. Turbulence at the sediment-water interface can have a substantial influence on phosphorus resuspension in the water column. Wind-driven sediment resuspension and biological activity (e.g., feeding and burrowing) of invertebrates and benthic fishes can be particularly important in shallow lakes and reservoirs. In deeper lakes and reservoirs, dissolved oxygen and iron (Fe) are often the most important mechanisms regulating phosphorus release from sediments. Iron is the major agent responsible for binding soluble phosphorus under aerobic (e.g., oxygenated) conditions. Because iron can bind about 10% of its own weight in phosphorus, iron availability can have an important influence on internal nutrient cycling (Jensen et al. 1992). Under anaerobic conditions, Fe^{+++} is reduced to Fe^{++}, releasing phosphorus to the overlying water. To understand the potential for internal nutrient loading, information on dissolved oxygen concentration near the water-sediment interface is required.

Nitrogen

Processes that govern nitrogen cycling are different from those that regulate phosphorus availability. Unlike phosphorus, nitrogen 1) does not significantly accumulate in reservoir sediments, 2) can disappear as gas into the atmosphere under reducing conditions and 3) can be utilized (i.e., fixed) by some cyanobacteria as a nutrient. Decomposition of organic matter generally occurs at the sediment-water interface resulting in production of ammonium (NH_4^+). Ammonium can diffuse into the water where it becomes readily available to algae. In aerobic sediments, ammonium can be converted to nitrate via microbial activity – a process called nitrification. Under anaerobic conditions (i.e., no dissolved oxygen), nitrate is converted to nitrite (denitrification) and ultimately to N_2 that is not readily available to green algae and can disappear as gas to the atmosphere (Scheffer 1998). Because denitrification works under anaerobic conditions, it occurs where conditions alternate between aerobic and anaerobic environments (e.g., the sediments). Hence, dissolved oxygen plays a critical role in denitrification, much like its role in sediment phosphorus release. Because some of the nitrogen entering a system may be lost as N_2 gas, nitrogen budgets can be difficult to measure in aquatic systems.

Turbidity

Water clarity is an important measure of water quality in lakes and reservoirs; it is desirable not only for aesthetic reasons but also because it has important implications for light attenuation and reservoir productivity. In practice, water clarity is usually measured as Secchi depth – the depth at which a 10 cm black & white disc can be viewed when lowered in the water. Because physical and biological components can affect water clarity, identifying the causes of turbidity can have important implications for impact assessments. Comparison of U.S. Bureau of Reclamation reservoirs in South Dakota, for example, reveals a large gradient in summer water clarity. Summer Secchi depths in Pactola, Deerfield, and Angostura reservoirs were 7, 5, and 3 meters, respectively (Chipps and Holcomb 2002; Chipps and Selch 2005). However, measurements of phytoplankton biomass (chlorophyll *a*) during the same time periods were generally similar among Pactola, Deerfield, and Angostura reservoirs at 1.1, 1.0, and 1.5 µg/L, suggesting that factors other than algae likely contribute to variability in water clarity.

Algae, detritus, and inorganic suspended solids are major constituents that affect both the absorption and scattering of light in water. The ability to predict the relative contribution of phytoplankton, organic detritus, and inorganic suspended solids on water clarity can provide an important tool for assessing seasonal and spatial variability in reservoir water clarity. A model developed by Buiteveld (1995) shows that water clarity, expressed as the inverse of Secchi depth (S_d), can be predicted as a linear function of algae, detritus and inorganic suspended solids concentration,

$$\frac{1}{S_d} = \sigma_c\, Chl + \sigma_d\, Det + \sigma_i\, ISS + \sigma_o \qquad (2)$$

where σ_c, σ_d, σ_i, and σ_o are regression constants, *Chl* is chlorophyll-a biomass (mg/L), *Det* is organic detritus (mg/L), and *ISS* is inorganic suspended solids (mg/L). For a given reservoir, field data can be used to develop parameters for this equation and used to assess the relative importance of factors affecting water clarity.

Zooplankton composition and abundance

Zooplankton composition and abundance can provide important information about the fish community of lakes and reservoirs. In lakes dominated by planktivorous fishes (i.e., plankton feeding fish), smaller cladocerans usually predominate because of size-selective predation by fish. Because small zooplankton are less efficient filter feeders on algae, the composition and size-structure of cladoceran populations can have an important impact on phytoplankton abundance; in lakes and reservoirs dominated by planktivorous fishes, algal abundance can be enhanced via trophic interactions that reduce abundance of large, filter-feeding *Daphnia* species. Moreover, high abundance of plankton-feeding fishes and small zooplankton taxa can have important implications for nutrient recycling. Because of allometric effects, nutrient excretion by small fish and zooplankton can be significantly higher than nutrient excretion by larger fish and zooplankton taxa – resulting in increased nutrient availability for algal growth.

Research Needs – Belle Fourche and Keyhole Reservoirs

To date, there has been no systematic effort to quantify spatiotemporal patterns in 1) nutrient availability, 2) algal biomass, 3) turbidity, or 4) zooplankton composition and abundance in Belle Fourche and Keyhole Reservoirs. Because nutrients, algae and zooplankton have important effects on reservoir productivity, and hence, water quality, lack of this information impedes RMPs for these units.

The purpose of this study is to document base-line conditions on water quality characteristics, algal biomass, turbidity and zooplankton composition in Belle Fourche and Keyhole reservoirs. Data collected in this study are comparable to that obtained from other Bureau of Reclamation projects in the Great Plains Region that include Pactola, Deerfield and Angostura reservoirs (Chipps and Holcomb 2002; Chipps and Selch 2005).

Research Objectives:

(1) Quantify spatiotemporal variation in water quality indicators for Belle Fourche and Keyhole reservoirs.

(2) Model nutrient dynamics in Belle Fourche and Keyhole reservoirs.

(3) Develop predictive models for quantifying factors affecting water clarity in Belle Fourche and Keyhole reservoirs.

Methods

Spatiotemporal variation in water quality indicators

Water quality characteristics were sampled monthly in Belle Fourche and Keyhole reservoirs from May through October, 2007. To account for spatial variability, five sites were sampled in Belle Fourche Reservoir and six sites were sampled in Keyhole Reservoir for water quality and biological data (Fig. 2). Sampling sites were widely dispersed across each reservoir and specific locations were documented using GPS. At each site, we collected two, 1 L water samples for analysis of total phosphorus, total Kjeldahl nitrogen, total suspended solids, inorganic suspended solids and chlorophyll *a* concentration. Water samples were collected at the surface and 1 m above the sediments at each site using a 2 L Kemmer bottle. Water samples for total phosphorus and total Kjeldahl nitrogen were then transferred to clean, 250 ml Nalgene bottles and frozen for later analysis. Chlorophyll *a* samples were collected by filtering 100-250 ml of water through a 0.7 µm Whatman GF/F filter, wrapping filters in aluminum foil, and then freezing filters for later analysis. Chlorophyll *a* concentration was measured using a Turner TD-700 fluorometer after 24 h of extraction in 90% acetone.

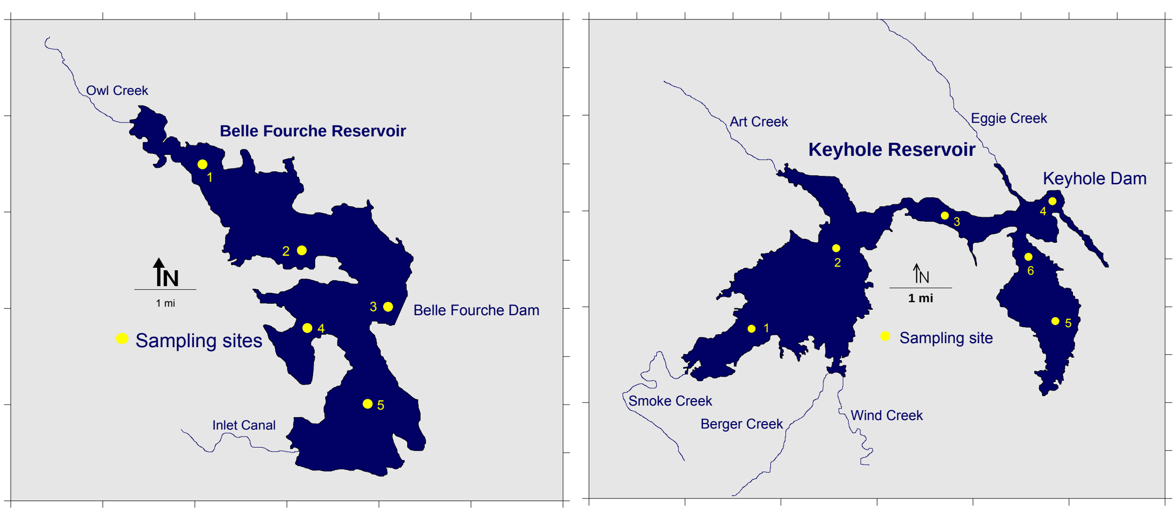

Figure 2. Map of Belle Fourche (left) and Keyhole (right) reservoirs showing locations of sites sampled from May to October, 2007.

Total suspended solids and inorganic suspended solids were determined using standard methods outlined in APHA (1998). Total phosphorus and total nitrogen (as TKN) were analyzed by the Olson Biochemistry Laboratory at South Dakota State University. Secchi depth and zooplankton were also collected at each site from May through October, 2007. Three replicate zooplankton samples were collected at each site using a 10 cm diameter, 150 µm mesh Wisconsin plankton net that was towed vertically from the lake bottom to the surface. Samples were preserved with 5% Lugol's solution and transported to the laboratory for identification and enumeration. Taxonomic identifications were made to species where possible and zooplankton abundance was calculated on a volumetric basis (no./L). Because *Daphnia spp*. can have an important influence on algae abundance, we evaluated spatial and temporal patterns in *Daphnia spp*. abundance from samples collected from each reservoir.

Water quality and zooplankton data were analyzed using a one-way analysis of variance, with sample date or sample location as grouping factors. Significant differences were evaluated using Tukey's multiple comparison test. Correlation analysis was used to explore relationships among nutrient concentrations, algal biomass, and zooplankton density.

Vertical profiles of water quality characteristics were monitored at two sampling stations; one site located near the dam, and one site located near the inlet (Fig. 2). Vertical profiles were taken at 0.5-1.5 m intervals using a YSI Model 650 DataSonde. Parameters measured by the DataSonde included dissolved oxygen (mg/L), water temperature (°C), pH, redox potential (mV), specific conductance (µS/cm), total dissolved solids (mg/L), and turbidity (NTU; Appendix A).

Data on water quality parameters and zooplankton abundance were used to generate spatially explicit maps for Belle Fourche and Keyhole reservoirs. Water quality data and zooplankton density were averaged for each sampling site (by date) and then interpolated between sampling stations using a 30 x 30 grid, generated using the point kringing method in Surfer© 8.0 software.

Nutrient loading

Measurements of nutrient inputs are necessary for determining nutrient loading rates in aquatic ecosystems. Water inflows and subsequent measures of nutrient loading rates were measured in June/July 2007 from major inlets in each reservoir (Fig. 2; sites 1). Belle Fourche Reservoir is located on Owl Creek, a tributary to the Belle Fourche River. The major inflow to Keyhole Reservoir is the Belle Fourche River. Other intermittent tributaries flow into the reservoirs but because of reduced or absent flows in June/July, these were not sampled (Fig. 2).

To estimate nutrient retention, phosphorus concentration was quantified from water samples taken at the inlets and outlets (immediately below the reservoir) in each reservoir. Using a variation of the Vollenweider model, mean summer phosphorus concentration (P) in Belle Fourche and Keyhole reservoirs was predicted as,

$$P = \frac{L(1-R)}{\tau \bar{z}}, \qquad (3)$$

where P is reservoir phosphorous concentration (g/m^3), L is areal annual phosphorus loading rate (g P/m^2/y), τ = hydraulic residence time (y), $\bar{z}$ = mean depth (m), and R = phosphorus retention rate (Dillon 1974). Phosphorus retention (R), in turn, was estimated as,

$$R = 1 - (q_o [P]_o / \sum q_i [P]_i), \qquad (4)$$

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). For modeling purposes, we defined annual rates in equations 3 and 4 (i.e., y) as the period from May-October, 2007. Inflow and outflow discharge data for May-October, 2007 were obtained from the U.S. Bureau of Reclamation.

Factors affecting water turbidity

Seasonal information on Secchi depth, phytoplankton biomass, detritus and inorganic suspended solids were used to develop an empirical model for predicting inverse Secchi (m^{-1}) as,

$$m^{-1} = \sigma_c\, Chl + \sigma_d\, Det + \sigma_i\, ISS, \qquad (5)$$

where *Chl* is chlorophyll *a* biomass (mg/L), *Det* is detritus (mg dry wt/L), and *ISS* is the concentration of inorganic suspended solids (mg dry wt/L). Detritus was not measured directly; rather, the concentration of detritus was estimated as the difference between ash free dry-weight of suspended solids (i.e., TSS-ISS) minus the dry-weight of algae (mg/L). The dry weight of algae, in turn, was calculated by assuming a dry-weight/chlorophyll *a* ratio of 70 (Scheffer 1998).

Results and Discussion

Spatiotemporal variation in water quality indicators

Temperature, dissolved oxygen, total suspended solids, and conductivity

In Belle Fourche Reservoir, vertical profiles of water temperature measured near the dam, show that the reservoir was generally isothermal from May to October, with water temperatures ranging from 11 °C in October to 26°C in July, 2007 (Fig. 3). Similarly, water temperature profiles showed that Keyhole Reservoir was generally well-mixed, with surface and bottom temperatures differing by less than 5° from May to October, 2007 (Fig. 3). Seasonal water temperatures in Keyhole Reservoir ranged from 14 °C in May to 24 °C in July.

Dissolved oxygen concentration varied with water depth for both reservoirs, particularly in summer months. In Belle Fourche Reservoir, dissolved oxygen was variable across months and within the water column and ranged from 1 mg/L in July to 16 mg/L in June. July was the only month where DO concentration near the lake bottom was low. In Keyhole reservoir, from early June through mid-August, dissolved oxygen concentrations were less than 4 mg/L at water depths >8.0 m (Fig. 4). We observed the lowest oxygen concentration (~1 mg/L) in mid August, at water depths of about 13 m. Although we found no evidence of summer ‘anoxia’ near the lake bottom, low oxygen concentrations (<3 mg/L) were commonly observed and could potentially limit deep-water fish habitat in Keyhole Reservoir.

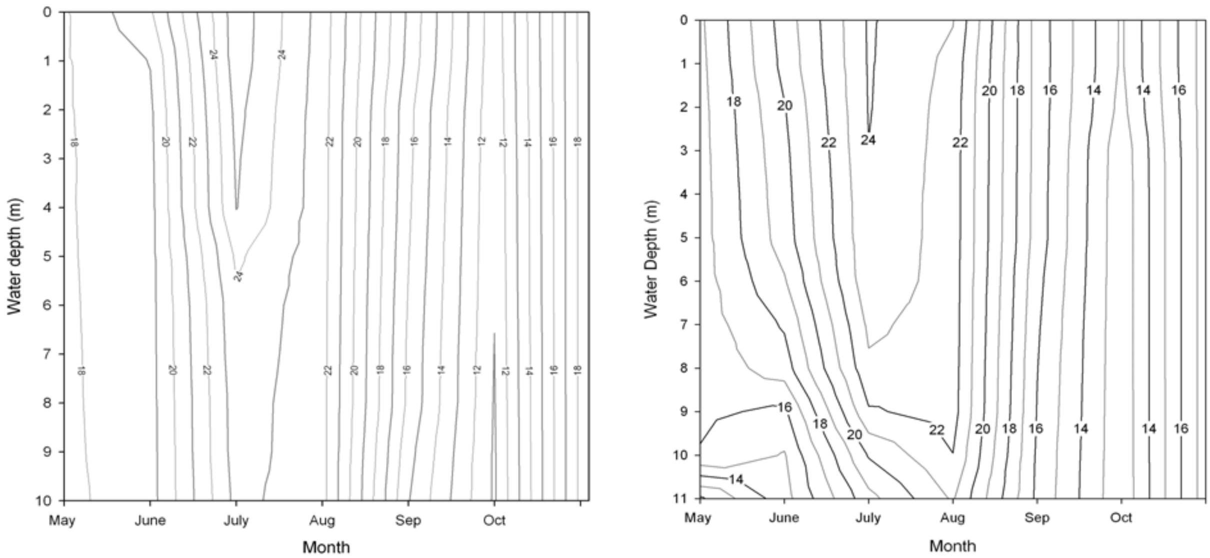

Figure 3. Water temperature (°C) isopleths for Belle Fourche (left) and Keyhole (right) reservoirs, May-October, 2007.

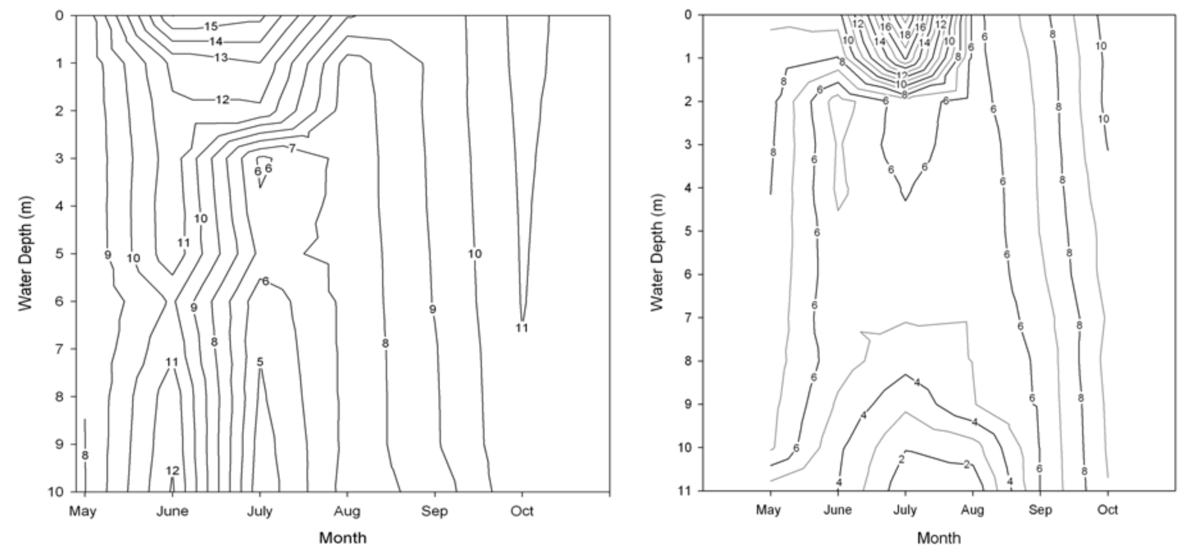

Figure 4. Dissolved oxygen (mg/L) isopleth for Belle Fourche (left) and Keyhole (right) reservoirs, May-October, 2007.

Average concentration of total suspended solids (TSS) was variable for Belle Fourche Reservoir from May to October, 2007 ranging from 3.4 in October to 14.5 mg/L in August ($F_{5,24}$=2.84, P=0.04; Fig. 5). Average monthly TSS was similar for Keyhole Reservoir ranging from 7.2 in October to 27.0 in May ($F_{5,30}$=1.16, P=0.35; Fig. 5). Water conductivity varied across months for both reservoirs, ranging from 1274.2 in June to 1411.9 μS/cm in October ($F_{5,11}$ =40.7, P=0.0002) in Belle Fourche Reservoir and 1969.7 in June to 2138.5 μS/cm in October ($F_{5,11}$=12.47, P<0.004) in Keyhole Reservoir (Fig. 6).

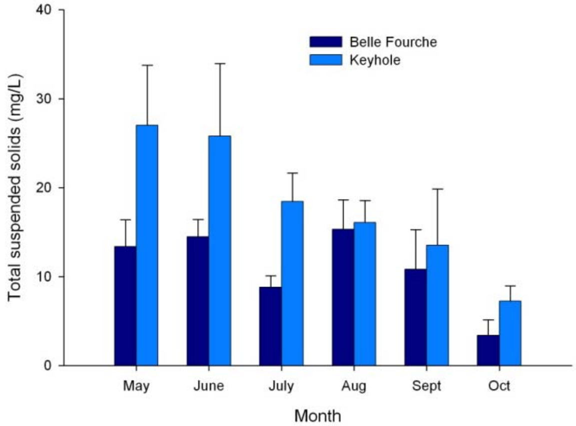

Figure 5. Mean total suspended solid (TSS) concentration measured in Belle Fourche and Keyhole reservoirs, May-October, 2007. Error bars represent 1 S.E.

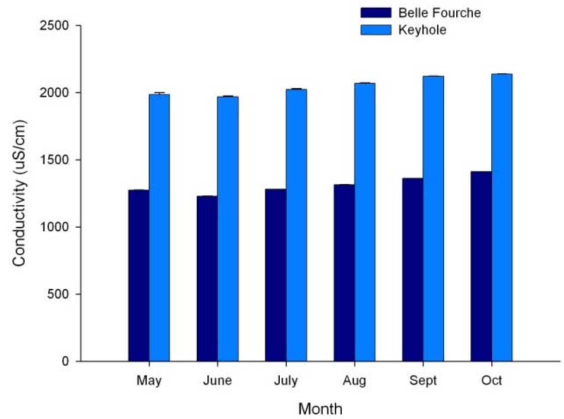

Figure 6. Mean water conductivity measured in Belle Fourche and Keyhole reservoirs, May-October, 2007. Error bars represent 1 S.E.

Concentration of total suspended solids (TSS) was highest near the inlets of both reservoirs, but did not vary significantly across sampling locations (Fig. 7). Average concentration of TSS for Belle Fourche Reservoir ranged from 8.42 mg/L at site 2 to 15.45 mg/L at site 1 ($F_{4,25}$=1.60, P= 0.478; Table 1). Average concentration of TSS was greater near the Owl Creek inlet in Belle Fourche Reservoir than at sites further down the reservoir (Fig. 7). Mean TSS concentration for Keyhole Reservoir ranged from 6.90 at site 6 to 32.33 mg/L at site 1 ($F_{5,30}$=1.60, P=0.19; Table 1). Average concentration of TSS was greater near the inlet than at sites located further downstream Keyhole Reservoir (Fig. 7).

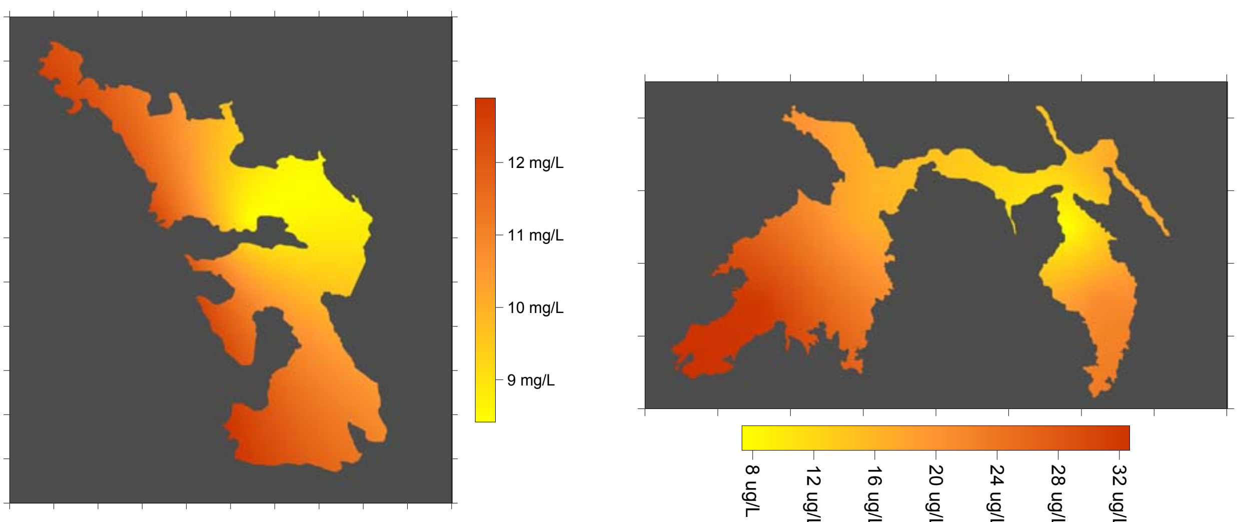

Figure 7. Mean total suspended solid (TSS) concentration in Belle Fourche (left) and Keyhole (right) reservoirs measured from May-October, 2007. Color scale represents TSS concentration in mg/L.

Table 1. Mean values for water quality and zooplankton abundance measured at five sites in Belle Fourche Reservoir and six sites in Keyhole Reservoir from May-October, 2007. For each variable, means with the same letter are not significantly different (Tukeys multiple comparison test; P.0.05). Values in parenthesis represent 1 S. E.

Reservoir	Site	Location Northing	Location Westing	Total suspended solids (mg/L)	Total P (ug/L)	TKN (ug/L)	N:P ratio	Chloro. a (ug/L)	Secchi depth (m)	Daphnia (no./L)
Belle Fourche Reservoir	1	44° 46’ 05.77”	103° 44’ 40.56”	15.46a (3.68)	26.00a (7.50)	223.00a (28.30)	13.58a (4.56)	2.18a (0.59)	0.47b (0.04)	5.86a (3.73)
	2	44° 42’ 36.27”	103° 42’ 39.91”	8.42a (1.22)	9.00a (1.50)	213.30a (42.00)	27.17a (8.66)	1.58a (0.39)	1.06a (0.14)	5.19a (4.06)
	3	44° 43’ 58.52”	103° 40’ 59.13”	9.33a (3.60)	10.00a (2.50)	195.30a (29.50)	18.24a (5.78)	2.24a (0.62)	1.27a (0.12)	8.86a (5.99)
	4	44° 43’ 45.29”	103° 42’ 25.70”	10.79a (2.43)	19.5a (8.90)	157.40a (17.1)	16.72a (5.37)	2.42a (0.69)	0.93ab (0.17)	7.64a (4.98)
	5	44° 42’ 24.50”	103° 41’ 14.58”	11.08a (2.55)	12.00a (1.70)	187.70a (13.00)	18.24a (4.16)	3.15a (0.86)	0.79ab (0.07)	4.99a (3.11)
Keyhole Reservoir	1	44° 20’ 56.88”	104° 51’ 47.80”	32.33a (10.43)	53.30a (13.8)	671.10a (78.00)	15.88a (2.70)	6.33a (1.41)	0.59a (0.18)	94.75a (14.13)
	2	44° 22’ 05.66”	104° 50’ 42.47”	17.21a (2.34)	31.70a (4.80)	605.80a (41.20)	22.15a (2.70)	5.58a (1.27)	0.80a (0.18)	81.67a (26.06)
	3	44° 22’ 31.85”	104° 48’ 45.84”	12.71a (2.32)	64.30a (28.70)	664.60a (74.20)	18.08a (3.714)	5.73a (1.55)	1.03a (0.08)	1.21b (0.51)
	4	44° 22’ 47.37”	104° 46’ 40.05”	17.06a (9.66)	46.50a (13.70)	637.30a (65.7)	18.653a (4.30)	5.04a (1.12)	1.07a (0.24)	0.57b (0.30)
	5	44° 20’ 45.27”	104° 46’ 42.37”	21.21a (1.51)	33.10a (5.80)	643.80a (40.00)	21.303a (2.47)	5.84a (1.19)	0.87a (0.14)	1.11b (0.49)
	6	44° 21’ 49.61”	104° 47’ 08.35”	6.96a (6.39)	29.30a (3.70)	672.20a (60.60)	24.04a (2.31)	4.87a (1.21)	1.32a (0.21)	2.38b (0.71)

Nutrients

Although variable, average monthly total phosphorus (TP) concentration was not statistically different in either reservoir from May-Oct, 2007. Average TP in Belle Fourche Reservoir ranged from 6 in July to 28 µg/L in August, 2007 ($F_{5,24}$=1.57, P=0.21; Fig. 8) and in Keyhole Reservoir ranged from 26 in October to 70 µg/L in May ($F_{5,30}$=1.38, P=0.26; Fig. 8). In contrast, total Kjeldahl nitrogen (TKN), representing the sum of organic nitrogen and ammonia nitrogen, varied significantly across months for Keyhole Reservoir ($F_{5,30}$=22.54, P<0.0001) and ranged from 557 ug/L in August to 893 ug/L in May (Fig. 9). TKN varied temporally in Belle Fourche Reservoir ($F_{5,24}$=1.76, P= 0.004) and ranged from 155 µg/L in September to 263 µg/L in July (Fig. 9).

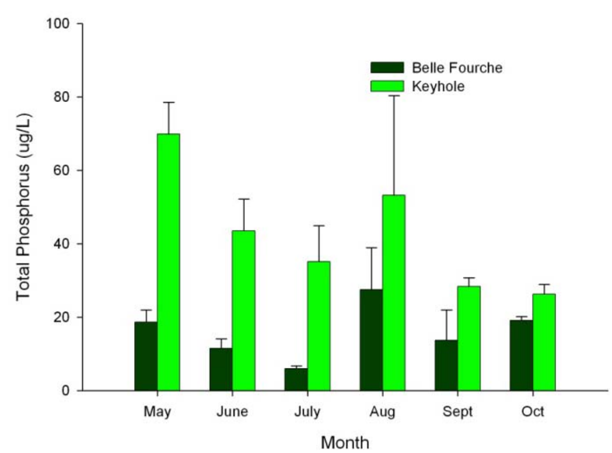

Figure 8. Mean total phosphorus concentration in Belle Fourche and Keyhole reservoirs, May-October, 2007.

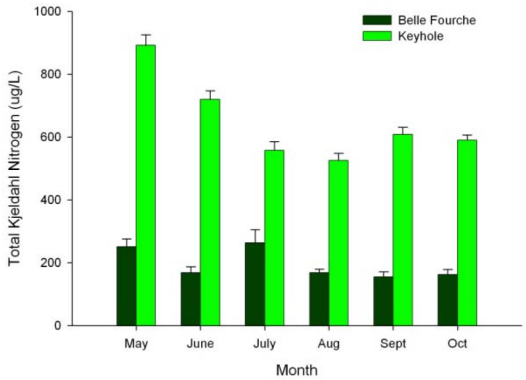

Figure 9. Mean total Kjeldahl nitrogen concentration in Belle Fourche and Keyhole reservoirs, May-October, 2007. Error bars represent 1 S.E.

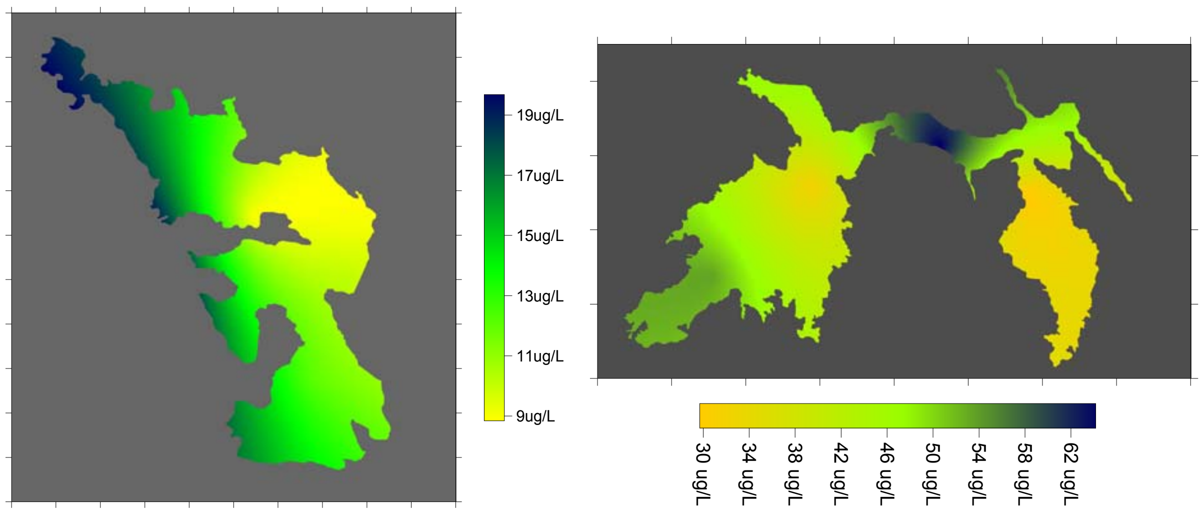

Figure 10. Mean total phosphorus concentration in Belle Fourche (left) and Keyhole (right) reservoirs measured from May-October, 2007. Color scale represents total phosphorus concentration in ug/L.

Spatial patterns in nutrient concentration were not significantly different among sites in each reservoir. Average TP concentration in Belle Fourche Reservoir ranged from 9.4 at site 2 to 26.0 µg/L at site 1 ($F_{4,25}$= 0.1.5, P=0.23) and in Keyhole Reservoir ranged from 29 at site 6 to 64 µg/L at site 3 ($F_{5,30}$= 0.96, P=0.46; Table 1; Fig. 10). Mean TKN concentration ranged from 157 µg/L at site 4 to 213 µg/L at site 2 ($F_{4,25}$= 0.82, P=0.23) for Belle Fourche Reservoir and 605 µg/L at site 2 to 672 µg/L at site 6 ($F_{5,30}$= 0.17, P=0.97) for Keyhole Reservoir (Table 1; Fig. 11).

The ratio of total nitrogen to total phosphorus is commonly used as an index of nutrient limitation. As a rule of thumb, N:P ratios greater than 15 generally indicate phosphorus limitation whereas N:P ratios less than 7 are indicative of nitrogen limitation. Although not statistically different (Belle Fourche, $F_{4,25}$= 0.73, P=0.58; Keyhole, $F_{5,30}$= 0.90, P=0.49; Table 1), mean N:P ratios were generally lower near the inlets as compared to N:P values observed in other areas of the reservoirs. Lower N:P ratio near the inlets was related to relatively high phosphorus concentration in these areas of the reservoirs.

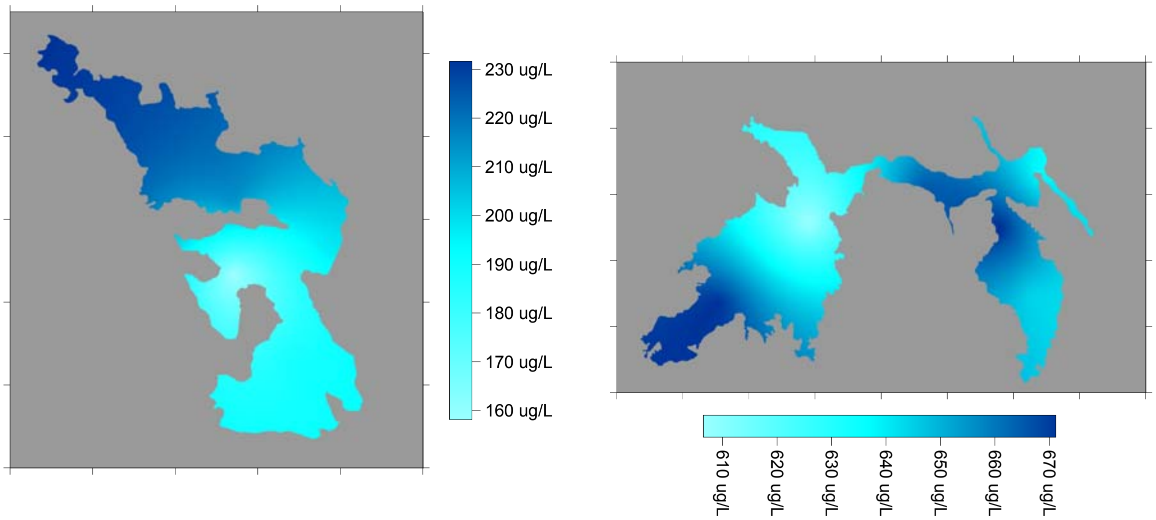

Figure 11. Mean total Kjeldahl nitrogen (TKN) concentration in Belle Fourche (left) and Keyhole (right) reservoirs measured from May-October, 2007. Color scale represents TKN concentration in µg/L.

Algae and water clarity

As expected, algal biomass varied appreciably in both reservoirs from May-October, 2007 (Belle Fourche, $F_{5,24}$= 12.83, P<0.0001; Keyhole, $F_{5,30}$= 13.00, P<0.0001; Table 1). Chlorophyll *a* biomass ranged from 0.49 µg/L in June to 4.26 µg/L in August in Belle Fourche Reservoir and from 1.61 µg/L in May to 8.65 µg/L in July in Keyhole Reservoir (Fig. 12). Peak algae biomass measured in Keyhole Reservoir (8.65 µg/L) was noticeably higher than that observed in other Bureau of Reclamation reservoirs (Angostura = 5.2 µg/L; Pactola = 0.86 µg/L; Deerfield = 1.84 µg/L). Mean monthly chlorophyll *a* biomass was poorly related to mean total phosphorus concentration in Belle Fourche (r=0.40, P=0.42) and Keyhole reservoirs (r=-0.75, P=0.08), implying that factors other than nutrient availability regulate algae abundance (Fig. 13).

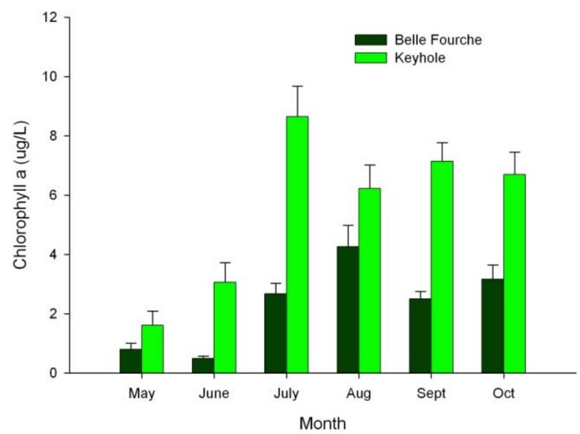

Figure 12. Mean monthly chlorophyll *a* concentration in Belle Fourche and Keyhole reservoirs, May-October, 2007. Error bars represent 1 S.E.

Although variable, water clarity, as indexed by Secchi depth, was not statistically different among months, for either reservoir (Belle Fourche, $F_{5,24}$=2.16, P=0.093; Keyhole, $F_{5,30}$=1.14,P=0.362; Table 1). In Belle Fourche Reservoir Secchi depth ranged from 0.67 m in October to 1.29 m in May and in Keyhole Reservoir ranged from 0.77 m in October to 1.24 m in June. Mean monthly Secchi depth varied inversely with algae biomass in both reservoirs from May to October, 2007 (Belle Fourche, r = -0.78, P = 0.06; Keyhole, r = -0.81, P=0.04; Fig. 14).

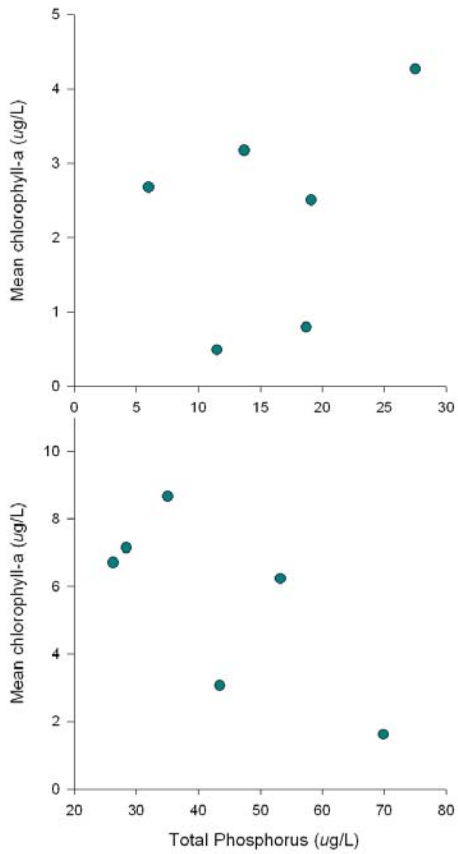

Figure 13. Biplot of mean chlorophyll a concentration versus total phosphorus concentration measured in Belle Fourche (top) and Keyhole (bottom) reservoirs, May-October 2007.

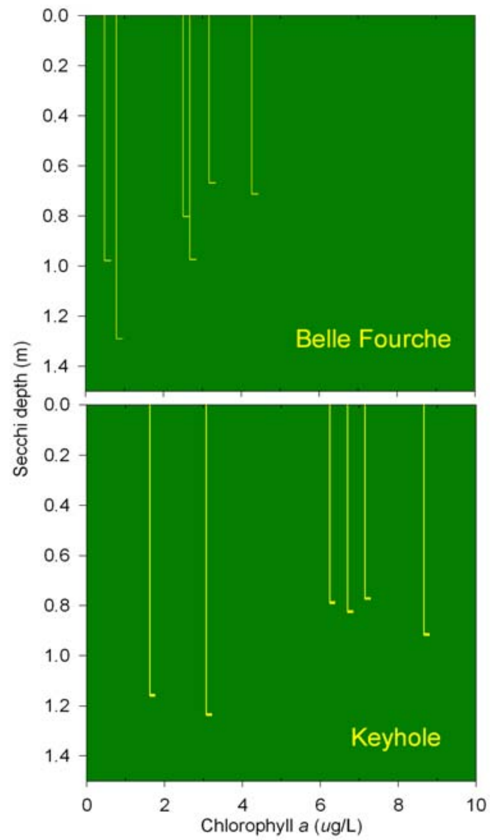

Figure 14. Mean Secchi depth versus mean chlorophyll a concentration in Belle Fourche (top) and Keyhole (bottom) reservoirs, May-October, 2007.

Mean chlorophyll *a* biomass was not statistically different among sampling sites in Belle Fourche ($F_{4,25}$=0.75, P=0.56) or Keyhole reservoirs ($F_{5,30}$=0.17, P=0.97; Table 1). Mean chlorophyll *a* concentration in Belle Fourche Reservoir ranged from 1.58 µg/L at site 2 to 3.15 µg/L at site 5 and in Keyhole Reservoir ranged from 4.87 at site 6 to 6.32 µg/L at site 1 (Fig. 15). Although variable, algal abundance was generally higher near major inlets in each reservoir and was lower in deeper waters near the dams.

Spatial analysis of Secchi depth showed that water clarity varied among sites in Belle Fourche Reservoir ($F_{5,25}$=2.2, P=0.001; Table 1) and was generally low near the inlet and high near the dam (Fig. 16). Secchi depth was not significantly different among sites in Keyhole Reservoir ($F_{5,30}$=1.99, P=0.108; Table 1), but like Bell Fourche, water clarity was lowest near the inlet and highest near the dam (Fig. 16).

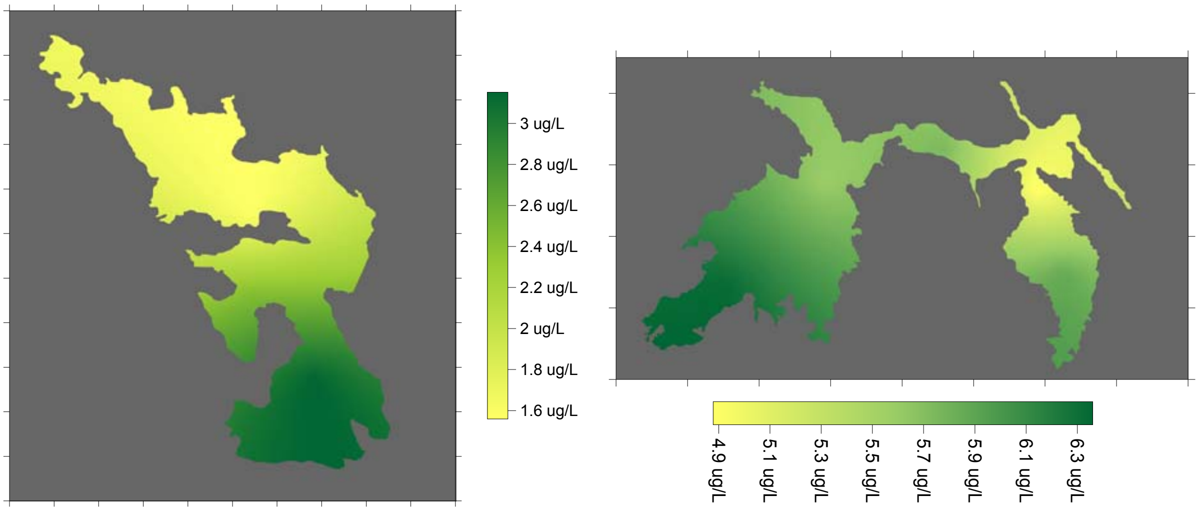

Figure 15. Mean chlorophyll a concentration in Belle Fourche (left) and Keyhole (right) reservoirs measured from May-October, 2007. Color scale represents chlorophyll a concentration in ug/L.

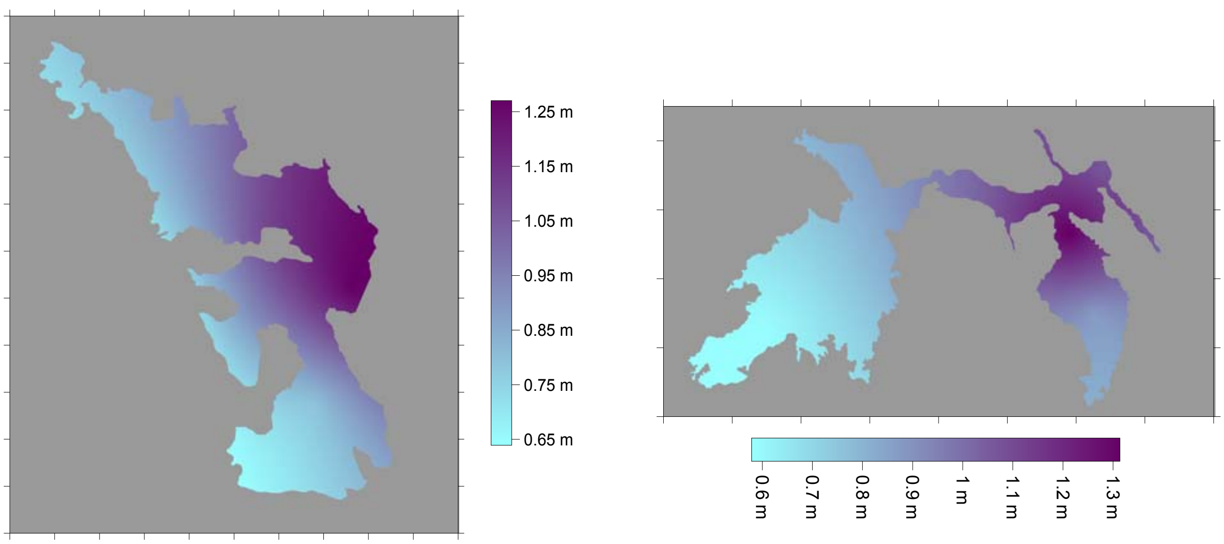

Figure 16. Mean Secchi depth in Belle Fourche (left) and Keyhole (right) reservoirs measured from May-October, 2007. Color scale represents Secchi depth in m.

Zooplankton

Nine species of pelagic zooplankton were identified from samples collected from Belle Fourche and Keyhole reservoirs (Appendix B). Because of their importance in regulating algae biomass, *Daphnia spp*. were analyzed to evaluate both temporal and spatial patterns in zooplankton abundance. Mean *Daphnia* densities varied by month in Belle Fourche Reservoir ($F_{5,24}$=28.52, P<0.0001; Fig. 17), with highest densities observed in May (20.8/L) and lowest densities observed in August (0.03/L), 2007. Mean *Daphnia* densities in Keyhole Reservoir were similar across months ($F_{5,30}$=0.18, P=0.97; Fig. 17) and ranged from 21.68/L in June to 40.92/L in August.

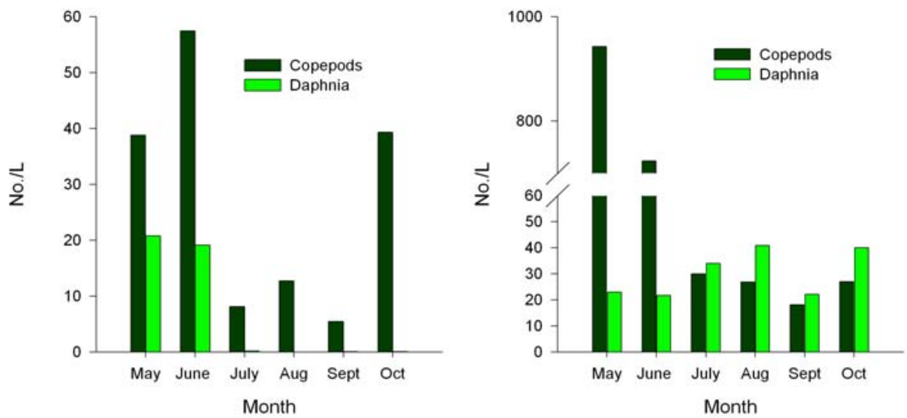

Fig 17. Mean abundance of copepod zooplankton and *Daphnia* in Belle Fourche (left) and Keyhole (right) reservoirs, May-October, 2007.

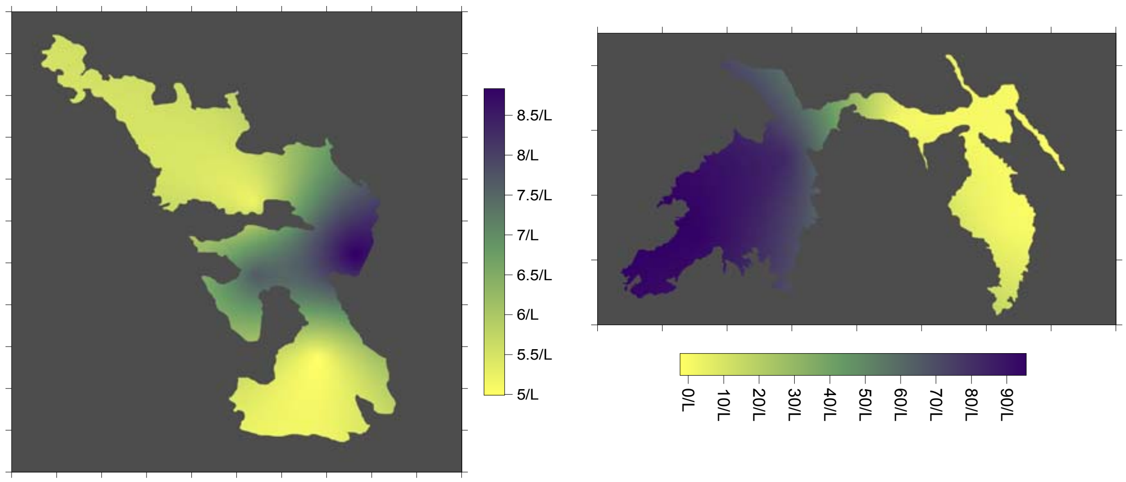

Fig 18. Spatial patterns in *Daphnia* density in Belle Fourche (left) and Keyhole reservoirs measured from May-October, 2007. Color scale represents daphnia density (no./L)

Although variable, we found no evidence that *Daphnia* abundance was different among sampling sites ($F_{4,25}$=0.12, P=0.975; Table 1) in Belle Fourche Reservoir (Fig. 18). In Keyhole Reservoir, however, *Daphnia* abundance was significantly different among sampling sites ($F_{5,30}$=13.85, P<0.0001; Fig. 18) with highest densities at the inlet (site 1) and lowest densities near the dam. Chlorophyll *a* biomass was inversely related to *Daphnia* abundance in both reservoirs, implying that local abundance of herbivorous *Daphnia* may have an important influence on spatial variability in algal biomass (Fig. 19).

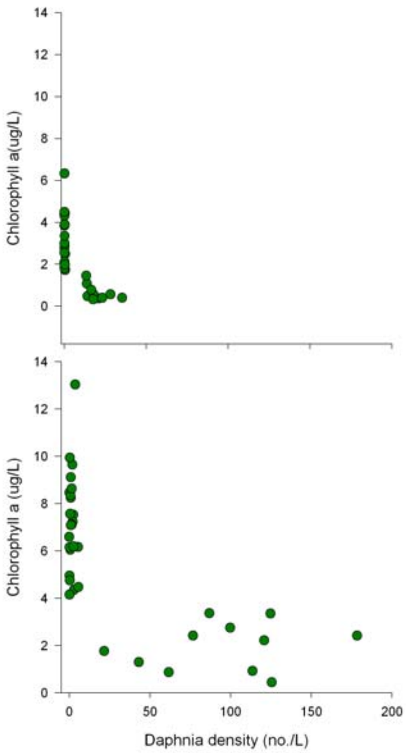

Fig 19. Relationship between chlorophyll a concentration and *Daphnia* density in Belle Fourche (top) and Keyhole (bottom) reservoirs, May-October, 2007.

Nutrient loading

Information on phosphorus concentration (inlet/outlet) was combined with data on inflows, outflows, and P retention rate to model average summer P concentration in Belle Fourche and Keyhole reservoirs (Table 2). For comparative purposes, we included modeling results from five Black Hills reservoirs reported in Chipps and Selch (2005). As shown in Figure 20, average summer P concentration in Black Hills reservoirs and Belle Fourche reservoir can be reasonably predicted by the Dillon-Rigler mass balance model. Modeling results for Keyhole Reservoir, however, showed that observed P concentration was much higher than model predictions (Fig. 20). Because phosphorus inputs were measured only from the inlet of the Belle Fourche River, it is likely that other sources contribute an appreciable amount of P to Keyhole Reservoir. To identify other primary nutrient sources to Keyhole reservoir, future sampling should focus on measuring phosphorus concentration near the mouths of Berger, Wind, Art, and Eggie creeks.

Table 2. Parameter values used to model phosphorus availability in Belle Fourche and Keyhole reservoirs. Mean tributary phosphorus inputs (P Loading) were measured from June-July, 2007 at the inlets. See text for details on the Dillon-Rigler model.

Reservoir	n	P Loading (mg P/m^2/d)	Areal annual P loading (mg P/m^2/y)	Hydraulic residence time (6 months)	Mean depth (m)	Phosphorus retention (R)
Belle Fourche	4	0.04	12.79	1.09	3.90	-0.70
Keyhole	4	0.06	20.15	6.71	7.62	0.64

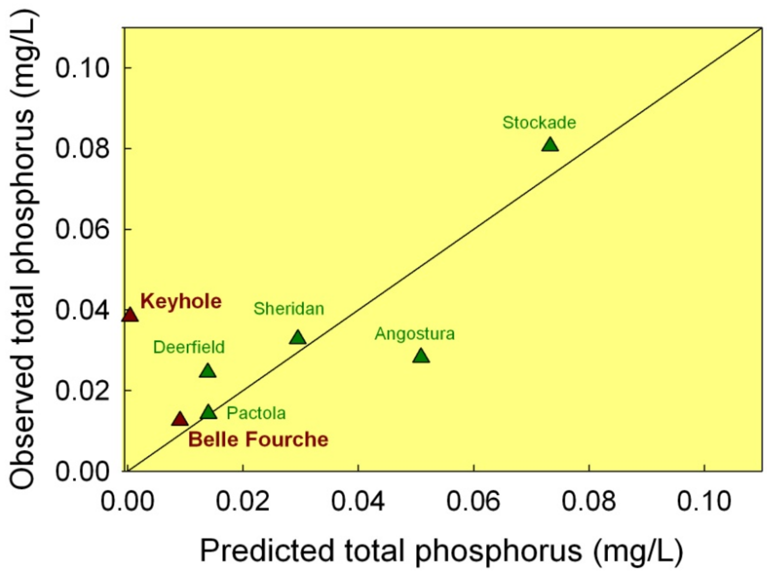

Fig 20. Relationship between observed and predicted total phosphorus concentration in Black Hills reservoirs, and Belle Fourche and Keyhole reservoirs. Predicted phosphorus concentration was estimated using the Dillon-Rigler mass balance model. Solid line represents 1:1 correspondence. See text for details.

Factors affecting water clarity

Concentrations of phytoplankton (*Chl*), inorganic suspended solids (*ISS*), and detritus (*Det*) were used to develop predictive equations for estimating water clarity in Belle Fourche and Keyhole reservoirs from May-October, 2007. For both reservoirs, *Chl*, *ISS* and *Det* explained >60% of the variation in water clarity (Table 3). Overall, the Belle Fourche model explained less variation in Secchi depth (R^2=0.62) than did the model for Keyhole reservoir (R^2=0.82; Table 3). Nonetheless, comparison of predicted versus observed Secchi depths in Belle Fourche and Keyhole reservoir shows that the model provided reasonable estimates of water clarity based on *Chl*, *ISS* and *Det* concentrations (Figs. 21 and 22). In general, the model performed better at predicting seasonal variation in Secchi depth than at predicting spatial variation (Figs. 21 and 22).

Table. 3. Parameter coefficients for the regression model $1/S = \sigma_c Chl + \sigma_I ISS + \sigma_D Det$ relating Secchi depth (S, m^{-1}) to concentrations of phytoplankton (*chl*, mg/L), Detritus (*Det*, mg/L) and inorganic suspended solids (*ISS*, mg/L) in Belle Fourche and Keyhole reservoirs.

Reservoir	σ_c	σ_I	σ_D	R^2
Belle Fourche	4.6	-0.1710	0.238	0.62
Keyhole	1.8	-0.0060	0.060	0.82

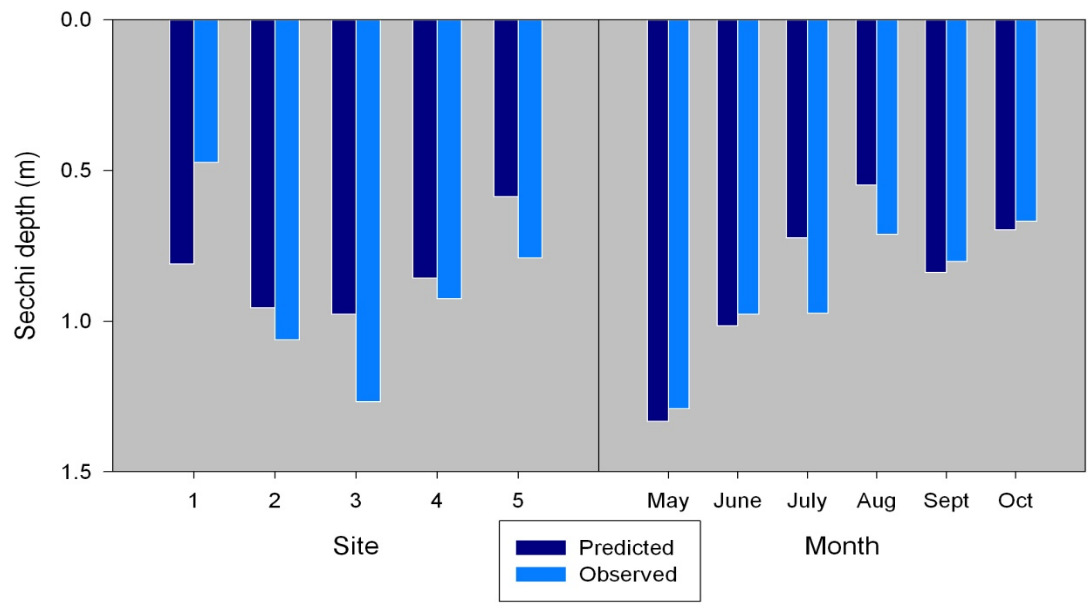

Fig 21. Comparison of predicted versus observed Secchi depths in Belle Fourche Reservoir. Left panel shows mean Secchi depths at each sampling location, averaged from May-October 2007. Right panel shows mean monthly values averaged across five sampling sites.

By accounting for temporal or spatial variability in seston fractions, the model can be used to evaluate the influence of each seston component on Secchi depth. In May and June, for example, water clarity in Belle Fourche Reservoir is affected mostly by suspended concentrations of detritus and inorganic solids (Table 4; Fig. 23). In summer and autumn months (July-October), however, phytoplankton has an important influence on Secchi depth.

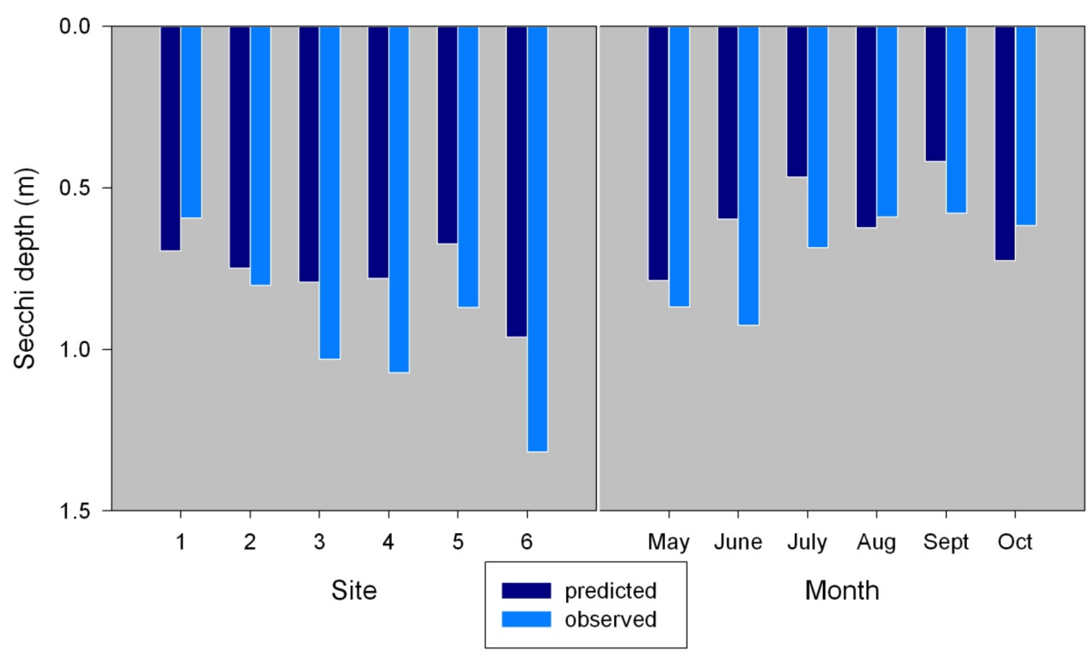

Fig. 22. Comparison of predicted versus observed Secchi depths in Keyhole Reservoir. Left panel shows mean Secchi depths at each sampling location, averaged from May-October 2007. Right panel shows mean monthly values averaged across five sampling sites.

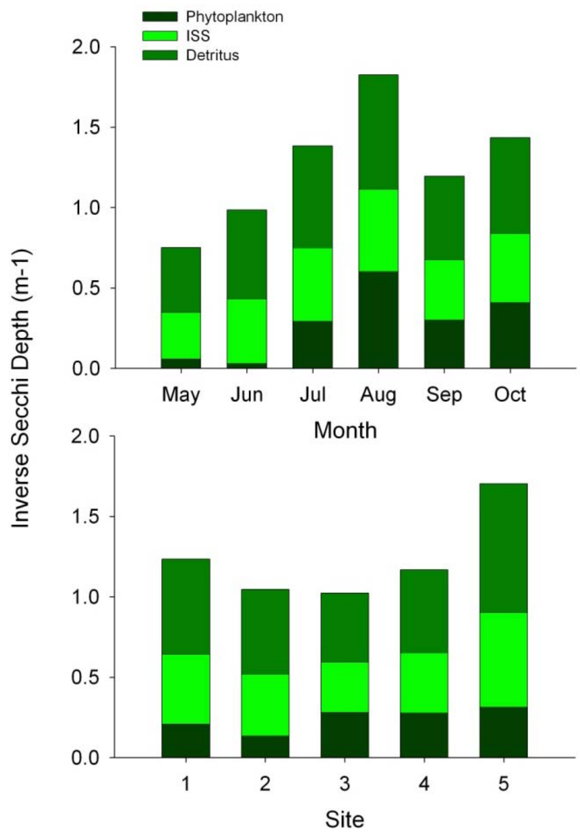

Fig. 23. Influence of phytoplankton, detritus and inorganic suspended solids (ISS) on mean Secchi depth (m^{-1}) averaged by month (top) or by sampling location (bottom) in Belle Fourche Reservoir, May-October, 2007. Inverse Secchi depth was predicted using coefficients in Table 3.

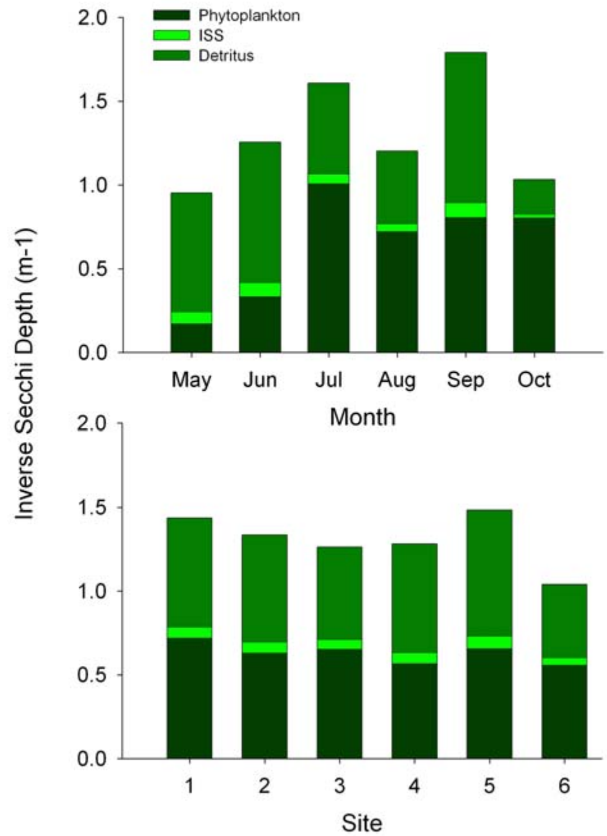

Fig 24. Influence of phytoplankton, detritus and inorganic suspended solids (ISS) on mean Secchi depth (m^{-1}) averaged by month (top) or by sampling location (bottom) in Keyhole Reservoir, 2007. Inverse Secchi depth was predicted using coefficients in Table 3.

Spatial patterns in water clarity show that for most areas of Belle Fourche Reservoir, detritus and to a lesser extent inorganic suspended solids, account for the largest proportion of turbidity (Fig. 23). Water clarity near Owl Creek canal inlet (site 1) is influenced mostly by inorganic suspended solids and detritus (Fig. 23). High concentrations of inorganic suspended solids were observed near the Owl Creek and are likely attributable to the high concentrations of suspended sediment flowing into Belle Fourche Reservoir from Owl Creek (Table 5).

Although Secchi depths were lower at the inlet site (site 1) in Belle Fourche Reservoir than at other locations in the reservoir, phytoplankton abundance was generally similar across sites– indicating that the light scattering properties of inorganic suspended solids do not necessarily reduce light availability for algae. Because Secchi readings are influenced by both light scattering and light absorption – it can be difficult to assess factors affecting water clarity unless, as shown here, the different seston fractions are evaluated.

Spatial patterns in water clarity show that for most areas of Keyhole Reservoir, phytoplankton and detritus accounted for the largest proportion of turbidity (Fig. 24) and showed little variation across the reservoir. Like Belle Fourche Reservoir, phytoplankton contribution increased in summer months (July-October), whereas detritus was important during spring (May-June) in Keyhole Reservoir.

Table 4. Average monthly seston concentration in Belle Fourche and Keyhole reservoirs, May to October, 2007. Values in parentheses represent 1 S.E.

	Month	Phytoplankton (mg dw/L)	Inorganic suspended solids (mg dw/L)	Detritus (mg dw/L)
Belle Fourche	May	0.056 (0.014)	7.35 (1.382)	7.294 (1.378)
	June	0.034 (0.006)	12.400 (2.826)	12.366 (2.827)
	July	0.187 (0.024)	7.800 (1.562)	7.80 (1.562)
	Aug	0.298 (0.050)	6.800 (1.685)	6.80 (1.685)
	Sept	0.175 (0.017)	4.200 (4.091)	4.025 (4.104)
	Oct	0.222 (0.033)	6.20 (1.393)	6.20 (1.392)
Keyhole	May	0.113 (0.037)	13.500 (5.958)	13.387 (5.971)
	June	0.214 (0.050)	15.833 (7.086)	15.619 (7.041)
	July	0.606 (0.078)	10.000 (1.442)	9.394 (1.416)
	Aug	0.436 (0.060)	8.000 (2.098)	7.564 (1.912)
	Sept	0.500 (0.048)	16.1667 (5.498)	15.987 (5.393)
	Oct	0.469 (0.058)	3.667 (0.882)	0.785 (0.785)

Table 5. Average seston concentration at sampling locations in Belle Fourche and Keyhole reservoirs, May to October, 2007. Values in parentheses represent 1 S.E.

	Site	Phytoplankton (mg dw/L)	Inorganic suspended solids (mg dw/L)	Detritus (mg dw/L)
Belle Fourche	1	0.153 (0.041)	8.458 (2.015)	8.305 (2.047)
	2	0.111 (0.027)	8.375 (2.737)	8.264 (2.749)
	3	0.157 (0.044)	4.6250 (1.648)	4.597 (1.627)
	4	0.169 (0.049)	6.125 (1.307)	6.034 (1.256)
	5	0.221 (0.06)	11.042 (1.979)	10.821 (1.995)
Keyhole	1	0.443 (0.099)	11.875 (7.158)	11.53 (7.119)
	2	0.391 (0.089)	11.792 (2.362)	11.401 (2.371)
	3	0.401 (0.108)	9.958 (2.096)	9.752 (1.932)
	4	0.353 (0.078)	11.7917 (5.395)	11.61 (5.423)
	5	0.409 (0.083)	13.875 (5.585)	13.466 (5.56)
	6	0.341 (0.085)	7.875 (2.473)	7.6785 (2.510)

Inter-reservoir comparisons

Mean Secchi depth varied considerably among Belle Fourche (0.90 m), Keyhole (0.95 m), Angostura (1.76 m), Pactola (5.48 m) and Deerfield (3.94) reservoirs (Table 6). Although water clarity was generally associated with reservoir trophic state (TSI) as indexed by chlorophyll *a* biomass (Table 6; Fig. 25), other factors also contributed to differences in observed water clarity. Information on seston concentration in Pactola, Deerfield, Angostura reservoirs was used to model the influence of different seston

Table 6. Mean secchi depth, chlorophyll a concentration, and TSI values measured in Belle Fourche, Keyhole, Angostura, Pactola and Deerfield reservoirs. Chlorophyll a samples were taken 1 m below the surface. Values in parentheses represent 1 S.E.

Reservoir	Month	n	Secchi depth (m)	Surface chlorophyll *a* (µg/L)	TSI_{CHL}
Belle Fourche	May	5	1.29	0.80 (0.2)	28.35
	Jun	5	0.98	0.49 (0.08)	23.62
	Jul	5	0.97	2.68 (0.35)	40.25
	Aug	5	0.71	4.26 (0.72)	44.83
	Sept	5	0.80	2.50 (0.24)	39.59
	Oct	5	0.67	3.17 (0.47)	41.92
	Mean		0.90	2.32 (0.34)	36.43
Keyhole	May	6	1.16	1.61 (0.48)	35.29
	Jun	6	1.24	3.06 (0.66)	41.58
	Jul	6	0.92	8.66 (1.02)	51.77
	Aug	6	0.79	6.23 (0.78)	48.55
	Sept	6	0.77	7.14 (0.63)	49.88
	Oct	6	0.82	6.70 (0.76)	49.25
	Mean		0.95	5.57 (0.72)	46.05
Angostura	May	5	4.22	0.49 (0.2)	23.60
	Jun	5	2.04	0.65 (0.03)	26.37
	Jul	5	1.06	4.04 (0.59)	44.30
	Aug	5	1.42	5.25 (0.72)	46.87
	Sept	5	0.96	4.46 (0.32)	45.27
	Oct	5	0.84	3.56 (0.84)	43.06
	Mean		1.76	3.07 (0.45)	38.24
Pactola	May	3	5.67	0.36 (0.02)	20.68
	Jun	3	4.28	0.60 (0.04)	25.64
	Jul	3	5.17	0.38 (0.01)	21.05
	Aug	3	5.34	0.49 (0.04)	23.53
	Sept	1	6.00	0.86 (0.00)	29.08
	Oct	3	6.42	0.41 (0.03)	21.95
	Mean		5.48	0.52 (0.08)	23.65
Deerfield	May	3	2.89	1.65 (0.13)	35.52
	Jun	3	2.77	1.82 ((0.13)	36.49
	Jul	3	4.50	0.75 (0.01)	27.73
	Aug	3	4.20	0.71 (0.05)	27.20
	Sept	0	no data	no data	no data
	Oct	3	5.32	1.84 (0.18)	36.60
	Mean		3.94	1.35 (0.26)	32.71

fractions on Secchi depth. Inter reservoir comparisons showed that ISS was a major constituent affecting mean Secchi depth in Angostura Reservoir from May-October. In contrast, phytoplankton and detritus have a stronger influence on water clarity in Pactola, Deerfield, and Keyhole reservoirs during the same time period. Water clarity in Belle Fourche Reservoir was influenced by almost equally by detritus, ISS and phytoplankton biomass (Fig. 26).

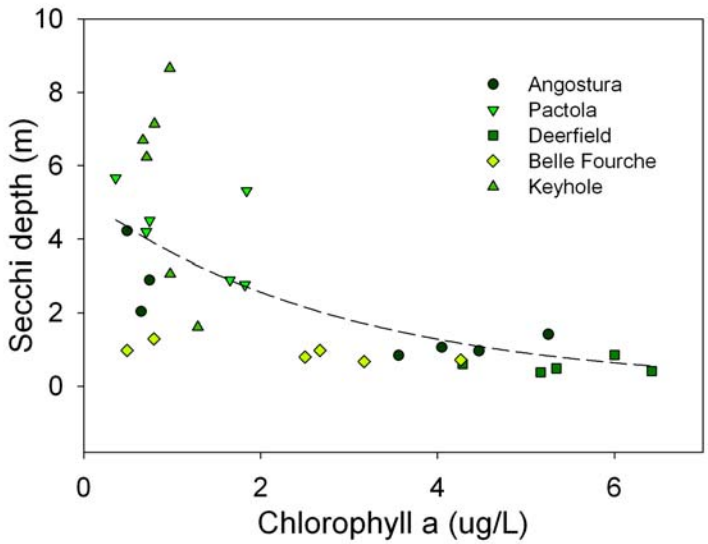

Fig 25. Relationship between observed Secchi depth and chlorophyll a biomass among Angostura, Pactola, Deerfield, Belle Fourche, and Keyhole reservoirs, South Dakota.

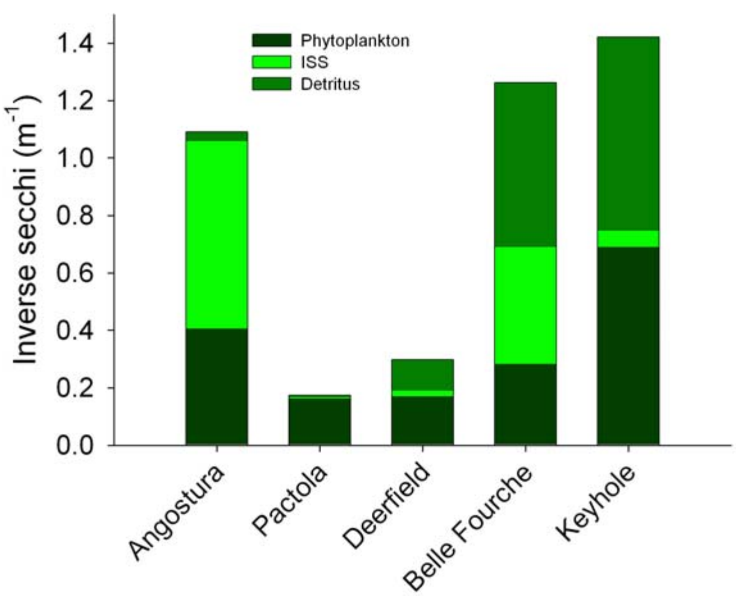

Fig 26. Relative contribution of phytoplankton, detritus and inorganic suspended solids to mean inverse Secchi depth in Angostura, Pactola, Deerfield , Belle Fourche, and Keyhole reservoirs.

Summary

Prior to this study, there was limited information regarding spatial and temporal patterns in nutrient levels, algae abundance and zooplankton density and composition in Belle Fourche and Keyhole reservoirs. Baseline water quality data are particularly important given recent concerns over water management alternatives and proposed coal bed methane extraction in the upper watershed. The purpose of this study was to provide an overview of limnological conditions in Belle Fourche and Keyhole reservoirs that will be useful for future monitoring and assessment.

Knowledge of spatiotemporal variation in water quality characteristics has important implications for characterizing limnological conditions. In Belle Fourche Reservoir, for example, we observed significant variation in seasonal measures of chlorophyll *a* concentration, *Daphnia* density, total suspended solids, and N:P ratios. In spring and early summer, water clarity was generally high, but decreased by late summer as algae biomass increased. Algae biomass, in turn, appeared to be regulated more by grazing pressure from herbivorous zooplankton (i.e., *Daphnia*) than by seasonal variability in nutrient concentration.

Spatial patterns in water clarity (Secchi depth), nutrient concentration, and total suspended solids were variable in Belle Fourche and Keyhole reservoirs. Concentrations of both total nitrogen and total suspended solids were generally higher near the inlets of each reservoir, corresponding to reduced water clarity in these areas.

Using modeling approaches, we found that nutrient concentration (total phosphorus) and water clarity (Secchi depth) can be reasonably predicted from empirical data. However, estimating mean summer nutrient concentration using the mass balance equation can be challenging if accurate estimates of phosphorus inputs are not obtained. In Keystone Reservoir, phosphorus concentration was underestimated using a mass-balance approach. This was likely attributed to phosphorus inputs (from other tributaries) not accounted for in the model. In Keyhole Reservoir, small tributaries such as Berger, Wind or Eggie creeks may provide important nutrient inputs to the reservoir and should be monitored in future efforts to model nutrient budgets.

Field data on chlorophyll *a* concentration (*Chl*) and total suspended solids (TSS) are often routinely collected in limnological studies. This information can be used to estimate the concentration of detritus (*Det*) and inorganic suspended solids (*ISS*). Combining data on *Chl*, *Det*, and *ISS*, we developed predictive models for estimating water clarity (Secchi depth) in Belle Fourche and Keyhole reservoirs. These models provide a tool for simulating the influence of different seston fractions (*Chl*, *Det*, and/or *ISS*) on Secchi depth in reservoirs and should prove useful for evaluating seasonal and/or spatial variability in water clarity.

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APPENDIX A

Monthly water quality data collected from sampling sites near the inlets (site 1) or dams (sites 3 or 4) in Belle Fourche and Keyhole reservoirs, May-October, 2007. Data represent average water column readings from vertical profiles measured using a YSI DataSonde, model 650. *September and October site 1 was located 0.5 miles downstream from original site 1 due to low water levels.

Reservoir	Date	Site	Total depth (m)	Mean water temperature (ºC)	Mean dissolved oxygen (mg/L)	Mean pH	Mean redox potential (mV)	Mean water conductivity (µS/cm)	Mean turbidity (NTU)
Belle Fourche	22-May	1	2.5	18.1	8.65	6.6	104	1257	14.3
		3	15	17.4	7.77	6.7	127	1276.5	5.3
	19-Jun	1	4.8	18.9	11.85	7.1	88.6	1247.8	17.7
		3	16	18.7	11.21	7.1	107.9	1224.2	10.1
	24-Jul	1	3.2	27.2	11.92	7.4	47.1	1287.7	17
		3	14.6	23.1	5.25	7.3	74.6	1279.2	10.1
	21-Aug	1	2	21.1	12.49	7	30.6	1304	45.3
		3	12.6	22.4	7.46	7.1	40.4	1316.8	7.5
	17-Sep	1*	1.3	15.9	9.74	7.3	6.2	1364	29.3
		3	11.6	15.8	8.88	7.2	-3.7	1360.3	6.3
	15-Oct	1*	1.3	10.6	11.61	7.6	-149.4	1416.5	15.6
		3	10.3	11.1	10.3	7.5	-127.8	1411.1	10.5
Keyhole	23-May	1	2.9	13.6	8.93	7.6	-17.5	1891.2	51.1
		4	14.2	16.8	9.21	6.8	73.2	1974	8.8
	20-Jun	1	3.1	18.7	14.83	7.2	88.6	1906	54.2
		4	14.7	16	4	7.3	89.3	1981.3	6.3
	25-Jul	1	0.9	23.3	18.97	7.3	48.1	2071.5	44.7
		4	13.7	20.9	5.39	7.3	67.6	2017.9	6
	22-Aug	1	1.7	22.5	7.82	7.3	31	2105	20.5
		4	13.6	21.9	4.12	7.3	38.2	2063.9	6.1
	18-Sep	1	2.2	15.9	9.35	7.1	29.3	2130.6	17.8
		4	13	16.2	6.62	7.3	0.3	2119.6	7.8
	15-Oct	1	2	12.1	10.67	7.6	-49.4	2155.5	9.8
		4	12.6	12.4	9.48	7.5	-50.1	2136.1	9.3

APPENDIX B

List of zooplankton species collected from U.S. Bureau of Reclamation reservoirs. Species presence is noted by an "X", whereas species absence is represented by "- -". Data from Belle Fourche and Keyhole reservoir were collected May-October, 2007 and data from Angostura, Pactola, and Deerfield reservoirs were collected May-October 2003. Two other Black Hills reservoirs (Sheridan and Stockade) are included for comparison.

Zooplankton Species	Belle Fourche	Keyhole	Angostura	Pactola	Deerfield	Sheridan	Stockade
Alona costata	——	——	——	X	X	X	X
Bosmina coregoni	——	——	X	——	——	——	——
B.hagmani	X	X	——	——	——	——	——
B.longirostris	——	——	X	X	X	X	X
Camtocercus macrurus	——	——	——	——	X	——	——
Ceriodaphnia lacustris	——	——	X	X	X	X	X
Chydorus sphaericus	——	——	——	X	X	X	X
Cyclops bicuspidatus	——	——	X	X	X	X	X
Daphnia g. mendotae	——	——	X	X	X	X	X
D. pulex	X	——	X	X	——	X	X
Daphnia sp.	X	X	——	——	——	——	——
Diaphanosoma brachyurum	X	X	X	——	——	——	——
Diaptomus siciloides	X	X	X	X	X	X	X
Ergasilus versicolor	——	——	X	——	——	——	——
Leptodiaptomus siciloides	——	X	——	——	——	——	——
Leptodora kindtii	X	X	——	——	——	——	——
Mesocyclops edax	X	X	X	——	——	——	——
Osphranticum labronectum	X	X	——	——	——	——	——