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Temporal Coherence of Water Quality Variables in a Suite of Missouri Reservoirs

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Abstract

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A six-year time series of water quality data from four eutrophic prairie reservoirs located in adjacent watersheds in northwest Missouri were analyzed for seasonal patterns and temporal coherence of temperature, dissolved oxygen, transparency, major ions, nutrients, suspended solids and chlorophyll. Water temperature was strongly seasonal as determined by the square of the average correlation of monthly means among years. No other variable was consistently seasonal in all four reservoirs, although two reservoirs exhibited strong seasonality for total and dissolved nitrogen and nitrate. Percent temporal coherence, measured as the square of the correlation between paired reservoir data sets, ranged from ≥98% for water temperature to <15% for chlorophyll. Ionic constituents (especially magnesium and alkalinity) and phosphorus fractions (dissolved, total and soluble reactive) had the strongest coherence (43-66%) averaged across all reservoir pairs. Algal biomass as chlorophyll and volatile solids had the weakest temporal coherence (0-21%). Other variables showed intermediate coherence (≥35%) for one or more reservoir pairs. Coherence strength between reservoirs was related to juxtaposition of catchments and probably reflects catchment-specific features. Temporal synchrony among these reservoirs may reflect a greater influence of external conditions on nutrients than transparency or algal biomass.

Key Words: temporal coherence, reservoirs, nutrients, chlorophyll, suspended solids

External inputs of energy and materials dominate many lake processes and contribute to the temporal variability characterizing lake water quality (Vollenweider 1975, Wetzel 2001). The magnitude of external inputs is determined by features such as flushing rate, catchment geology and land use that govern export of materials from watersheds to lakes (Beaulac and Reckhow 1982, Duarte and Kalff 1989, Jones *et al.* 2004). Lake response to external inputs depends on morphological factors such as water depth and volume that determine input dilution. Small, shallow basins with large catchments are most responsive to external conditions. Such features typify thousands of small artificial lakes common across much of the United States and many regions of the world (Thornton *et al.* 1990).

In Missouri there are about 3000 artificial lakes (not including small ponds <2 ha), the majority of which have surface areas ≤4 ha, mean depths ≤2 m and flushing rates ≥1.6/year (Missouri Department of Natural Resources, Dam Safety Data Base). Sensitivity of water quality to external controls is a principal assumption underlying lake management that focuses on limiting nutrient and sediment inputs as a means of controlling algal biomass and improving transparency (Hoyer and Jones 1983, Jones and Knowlton 1993). Among reservoirs statewide, external conditions govern nutrients and suspended solids, which are highly correlated to catchment land use, especially cropland (Jones *et al.* 2004, Jones and Knowlton 2005a). Land use is less influential, however, among predominantly eutrophic reservoirs in the agricultural prairie regions of the state (Jones *et al.* unpublished manuscript). This difference may reflect lower sensitivity of eutrophic lakes to external inputs due to the availability of internal nutrient supplies (Welch and Jacoby 2001). If so, prairie reservoirs may be less responsive to control of external inputs than Missouri reservoirs in general, requiring other approaches to lake management.

Temporal coherence, the tendency of nearby lakes to vary synchronously over time (Magnuson *et al.* 1990), provides a clue to the role of external influences on prairie reservoirs.

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Lack of synchrony could stem from dominance of internal processes or to external effects that vary greatly among lakes. But a high degree of synchrony would clearly suggest a dominant role of external conditions operating similarly over the region (George *et al.* 2000, Fölster *et al.* 2005, Chrzanowski and Grover 2005). To explore the role of external influences on water quality in eutrophic prairie reservoirs, we analyzed temporal coherence in monitoring data from four reservoirs near the City of Cameron in northwest Missouri. The reservoirs are in adjacent catchments less than 4 km apart (Fig. 1) and were sampled almost synoptically an average of 17 times annually during 1998-2003. In this paper we compare temporal coherence of water temperature, dissolved oxygen, and concentrations of major ions, total and dissolved nutrients, suspended solids, transparency and chlorophyll to explore the question of external influences. We assume that a high degree of synchrony is evidence of external control operating similarly across lakes and watersheds and thus optimally suited for prediction and regionally applied management schemes. Lack of synchrony suggests internal controls or external influences that are lake-specific and thus less amenable to prediction and management.

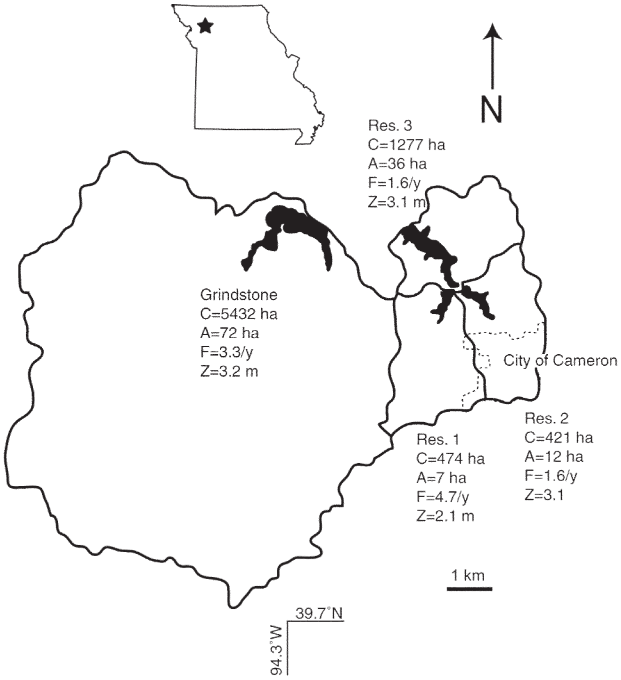

Figure 1.-City of Cameron Reservoirs and catchments. C=catchment area, A=reservoir surface area, F=nominal flushing rate, Z=mean depth.

Study Sites

The City of Cameron reservoirs, Reservoir 1, 2, 3 and Grindstone, are in northwest Missouri (39.77°N, 94.28°W) in the headwaters of the Grindstone Creek watershed (Fig. 1). Reservoir 3 (area=36 ha) shares 70% of its catchment with Reservoirs 1 (7 ha) and 2 (12 ha), both located just upstream above a fork in the principal tributary of Reservoir 3. Most of the unimpounded portion of the Reservoir 3 catchment lies to the northeast bordering the catchment of Reservoir 2. Grindstone Reservoir (72 ha) is ~1.5 km west of Reservoir 3 in the adjacent watershed.

Collectively, land use in these catchments is dominated by agriculture with crop land and pasture making up 69-93% of total area, but over a third of the catchment of Reservoir 2 is within the city limits of Cameron. Mean depths of the lakes range from 2.1 m (Reservoir 1) to 3.2 m (Grindstone) at full pool, but reservoir volumes fluctuate by a factor of ~2-3 in response to inflow and extraction of water. Water is pumped to the municipal water plant from Reservoir 3 (~5000 m^3/day). To maintain its volume, water is occasionally pumped (~11,000 m^3/day) to its principal tributary (just below Reservoir 1) from Grindstone. In 2002 and 2003 total volumes pumped annually were approximately equal to the full pool volume of Reservoir 3. To make room for spring inflows, water is sometimes released in winter from Reservoirs 1 and 2 at rates up to 2000 m^3/day per lake. The water released or pumped to Reservoir 3 usually represents no more than a ~1-2%/day increase in lake volume. In comparison, inflows from storm runoff sometimes yield volume increases of ~20%/day in the three headwater reservoirs. Nominal flushing rates – average runoff (14 cm/y) times catchment area divided by full pool reservoir volume – range from 1.6/y for Reservoirs 2 and 3 to 4.7/y for Reservoir 1 (Fig. 1), but actual flushing rates are unknown. Inflows and outflows of the reservoirs have not been gauged and records of water levels, drawdowns and pumping rates are complete only for years 2002-2003. In some years (*e.g.*, 2002), pumping from Grindstone constitutes the principle input of water to Reservoir 3. All streams in the study area are intermittent except Grindstone Creek, which flows perennially for a distance of ≈ 3 km above Grindstone reservoir.

Reservoir 1 is polymictic while Reservoir 2 has stable thermal stratification during April-October in most years. Grindstone is usually stratified during May-September. Reservoir 3 is circulated artificially by compressed air and remains nearly homothermal except during brief periods when circulation is interrupted to service equipment. When stratified, bottom waters of all four lakes deoxygenate rapidly. Hypolimia of Reservoir 2 and Grindstone are usually anoxic.

Field and Laboratory Methods

Reservoirs were sampled near the dam, in late winter through late fall 1998-2003 at about 2-week intervals. Temperature, dissolved oxygen and specific conductance profiles were recorded using a YSI-85 portable instrument. Water clarity was measured using a 20 cm Secchi disk. Water samples (4 L) usually were collected from the surface, the Secchi depth and twice the Secchi depth, but in some instances only surface samples were taken. Samples were held on ice or refrigerated until processing, usually the same day. Raw water was used for analysis of total phosphorus (TP), total nitrogen (TN), alkalinity, chlorophyll *a* (Chl - Pall AE filters) and suspended solids (Whatman GF/C filters). Filtrates (GF/C filters) were used for analysis of dissolved total phosphorus (dTP), soluble reactive phosphorus (SRP), total dissolved nitrogen (dTN), nitrate/nitrite nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), silica (SiO_2), chloride, calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K). On some sampling dates, one or more variables were not measured due to technical failures. Ammonium was not measured after May 2003.

Phosphorus was measured by the ascorbic acid method (APHA 1989) following persulfate digestion (except SRP). Nitrogen (TN and dTN) was measured by second-derivative spectroscopy following persulfate digestion (D'Elia *et al.* 1977, Simal *et al.* 1985). A Lachat QuickChem® flow injection autoanalyzer was used to measure NO_3-N (cadmium reduction; Pritzlaff 2003), NH_4-N (Berthelot reaction; Diamond 2001) chloride (mercuric thiocyanate method; Diamond 1994) and silica (ammonium molybdate; McKnight 2000). Chlorophyll was measured fluorometrically after extraction in hot ethanol (Knowlton 1984, Sartory and Grobbelaar 1984). Total, volatile and nonvolatile suspended solids (TSS, VSS, NVSS) were measured gravimetrically (APHA 1989). Alkalinity was measured by potentiometric titration (APHA 1989), and cations were determined by inductively coupled plasma, atomic emissions spectroscopy (Liberty model RL ICP-AES, Varian, Inc.).

Data Analysis

Measurements from all depths were averaged to represent each reservoir on a given day. Observations were paired by sampling event using only observations in which all four reservoirs were sampled within a three-day span. Reservoirs were usually sampled on the same day, but about a forth of the observations, predominately in 2000 and 2001, were collected over longer periods. Thus the number of paired observations ranged from 8 in 2000 to 32 in 2003 with a mean of 17/y. Most years lacked paired observations in December-January. The annual span of paired observations ranged from 207 to 313 days (mean=262 days) beginning as late as 26 March (2001) and ending as early as 10 October (2000) with intervals averaging 16 days between paired samples (range 4-51 days).

Most variables had log-normal distributions and were transformed to base 10 logarithms before analysis. Exceptions were temperature, Secchi depth and concentrations of Mg, Ca and Na. Observations with undetectable concentrations of NO_3-N (<0.01 mg/L), NH_4-N (<0.01 mg/L), SRP (<1 µg/ L), or SiO_2 (<0.01 mg/L) were set at their respective detection limits for analysis. Paired observations for the six lake-pair combinations were used to calculate Pearson's correlation coefficient (r), the square of which (r^2) represents the proportion of temporal variability shared by the two reservoirs in the pair. Seasonality of temporal variation for each variable and reservoir was evaluated by measuring the average correlation between monthly means for all possible pairs of years. Observations for each year were averaged by month, monthly means for each year were paired with means from all other years (15 total pairings for the six years of data), and the simple correlation between the paired monthly means was calculated. The average correlation coefficient for each reservoir and variable was squared to represent the percent of temporal variation due to repeated seasonal patterns (seasonality coefficient). For both temporal coherence and seasonality coefficients, negative correlations were assigned an r^2 value of zero. Scatter plots of the paired data were examined to identify potentially influential outlyers, and time series plots were used to characterize details of temporal patterns. Multiple regression analysis using $\log_{10}$-transformed data were used to compare the effects of mineral turbidity (NVSS) and algal biomass (Chl) on Secchi depth.

Results

During the study, conditions in the four reservoirs varied widely (Table 1). Dissolved nutrients (dTN, NO_3-N, NH_4-N, dTP, SRP, SiO_2), TP, Chl, TSS and NVSS exhibited standard deviations >50% of their respective means in most or all the reservoirs. With respect to nutrient concentrations, Reservoir 1 and Grindstone are among the most eutrophic impoundments in Missouri, with mean TP and TN in the upper 3% of reservoirs in the state (Jones and Knowlton 1993). Reservoirs 2 and 3 were usually less turbid and nutrient-rich than Reservoir 1 and Grindstone, but all four reservoirs are highly eutrophic. Chl exceeded 40 µg/L in >25% of observations in Reservoirs 1, 3 and Grindstone and in 11% of observations in 2. Salinity variables were comparable among the four reservoirs, except for Na and chloride (Cl) which were consistently greater in Reservoir 2, probably because of road salt from the City of Cameron. Transparency in all four reservoirs was closely related to concentrations of mineral seston as measured by NVSS. In lake-specific regression models using log-transformed data, NVSS accounted for 62-74% of variation in Secchi. As a second independent variable, Chl was significant only in Reservoir 2, accounting for only 3% of the variation in transparency not due to NVSS. Combining data from all four reservoirs the regression model was:

$$\log_{10} \text{Secchi} = 0.23 - 0.55 \times \log_{10} \text{NVSS}$$

(n=374, RMSE=0.12, p<0.0001). Chl was not significant (p=0.19) as a second independent variable.

Table 1.-Means and standard deviations of water quality variables in Cameron City reservoirs, 1998-2003 (Grindstone=GR).

	n	1	2	3	GR
Temp. (°C)	88	20.8 ±7.9	20.6 ±7.7	20.5 ±7.8	20.0 ±7.7
D.O. (mg/L)	88	8.6 ±3.2	8.7 ±2.4	8.6 ±2.5	8.3 ±2.6
TN (mg/L)	101	1.4 ±0.6	1.0 ±0.3	1.0 ±0.4	2.1 ±1.2
dTN (mg/L)	101	1.0 ±0.6	0.7 ±0.3	0.8 ±0.4	1.7 ±1.2
NO_3-N (mg/L)	101	0.4 ±0.6	0.3 ±0.3	0.2 ±0.4	1.1 ±1.3
NH_4-N (mg/L)	80	0.1 ±0.1	0.1 ±0.1	0.1 ±0.1	0.1 ±0.2
TP (µg/L)	99	171.8 ±98.0	55.5 ±31.1	88.3 ±37.7	163.8 ±93.1
dTP (µg/L)	97	81.6 ±72.4	20.2 ±20.5	34.4 ±30.1	92.2 ±85.6
SRP (µg/L)	101	60.2 ±75.3	7.9 ±17.6	17.8 ±27.7	71.1 ±86.1
Chl (µg/L)	98	41.4 ±37.4	21.1 ±13.7	31.4 ±23.6	41.1 ±37.6
TSS (mg/L)	101	26.7 ±17.5	11.8 ±12.3	16.2 ±6.1	23.0 ±13.5
NVSS (mg/L)	101	18.8 ±15.8	7.5 ±11.0	11.1 ±5.2	16.4 ±12.7
VSS (mg/L)	101	7.9 ±4.0	4.2 ±2.0	5.2 ±2.5	6.6 ±2.7
SiO_2 (mg/L)	100	3.5 ±3.0	1.4 ±1.8	1.9 ±1.7	3.8 ±3.1
Cl (mg/L)	98	11.9 ±4.2	19.4 ±6.1	13.5 ±2.8	10.8 ±3.3
Alk (mg/L)[1]	95	109.2 ±15.9	108.8 ±14.1	110.1 ±9.4	98.6 ±16.8
K (mg/L)	98	7.1 ±1.3	5.8 ±1.3	6.7 ±1.0	6.4 ±1.2
Mg (mg/L)	98	8.1 ±1.4	7.3 ±1.1	7.7 ±0.9	7.4 ±1.4
Ca (mg/L)	98	38.4 ±6.4	39.2 ±6.7	39.2 ±4.6	33.5 ±6.0
Na (mg/L)	98	11.1 ±3.3	15.2 ±4.1	11.2 ±2.4	9.4 ±2.9
Secchi (m)	91	0.4 ±0.2	0.8 ±0.3	0.5 ±0.2	0.4 ±0.2

[1] Alkalinity as $CaCO_3$

Seasonality

Water temperature provides an example of temporal variability dominated by a seasonal pattern. Monthly mean temperatures paired among years were strongly correlated yielding seasonality coefficients (square of the mean correlation) of 91-93% for the four reservoirs (Table 2). Other than temperature, however, no variable was consistently seasonal in these lakes, although some parameters showed repeated temporal patterns in one or more impoundments. In Reservoir 2, NO_3-N, dTN and TN were moderately to strongly seasonal (40-69%) with peak concentrations usually measured in March-April and with no measurable NO_3-N in summer (Fig. 2a). The same variables were also strongly seasonal in Grindstone (seasonality coefficients 56-63%) consistently peaking in May-June with low values in summer. In contrast, nitrogen peaks were much less predictable in reservoirs 1 and 3. Although these lakes usually lost NO_3-N in summer (*e.g.*, Fig. 2b), undetectable concentrations were observed irregularly throughout the year.

In the three headwater reservoirs, seasonality accounted for 22-51% of the temporal variation in alkalinity and Ca, with values $\geq$44% in Reservoir 2. Concentrations were usually greatest early in the year and declined through the summer with recovery in autumn some years. Mg displayed a similar pattern in Reservoir 1 (34% seasonality). Reservoir 2 showed moderate seasonality (35%) for NVSS typified by maximum concentrations in spring and minima in late summer. This pattern in NVSS was also somewhat evident in Grindstone (23% seasonality). But for other variables and impoundments, no more than 21% of the variation was reproducibly seasonal. Even dissolved oxygen (DO), for which temperature controls saturation kinetics, was only weakly ($\leq$17%) seasonal. Time series of DO showed consistently high concentrations in winter, but in these eutrophic systems, summer concentrations were often supersaturated. For most variables, time series were dominated by peaks or valleys often associated with rainfall events that occur throughout the year but vary in magnitude and effect on individual variables (*e.g.*, Fig. 2).

Table 2.-Seasonality coefficients of water quality variables in the City of Cameron reservoirs during 1998-2003.

	1	2	3	GR
Temp	0.91	0.92	0.93	0.91
D.O.	0.17	0.08	0.12	0.10
TN	0.08	0.40	0.04	0.57
dTN	0.08	0.50	0.03	0.63
NO_3-N	0.06	0.69	0.04	0.56
NH_4-N	0.00	0.20	0.13	0.02
TP	0.00	0.06	0.00	0.01
dTP	0.02	0.11	0.00	0.03
SRP	0.00	0.00	0.00	0.02
Chl	0.01	0.13	0.11	0.00
TSS	0.12	0.18	0.12	0.16
VSS	0.01	0.09	0.06	0.00
NVSS	0.17	0.35	0.04	0.23
SiO_2	0.00	0.04	0.15	0.02
Cl	0.21	0.11	0.05	0.17
Alk	0.22	0.44	0.05	0.28
K	0.00	0.02	0.00	0.01
Mg	0.34	0.20	0.03	0.20
Na	0.12	0.18	0.01	0.17
Ca	0.33	0.51	0.15	0.34
Secchi	0.02	0.00	0.10	0.10

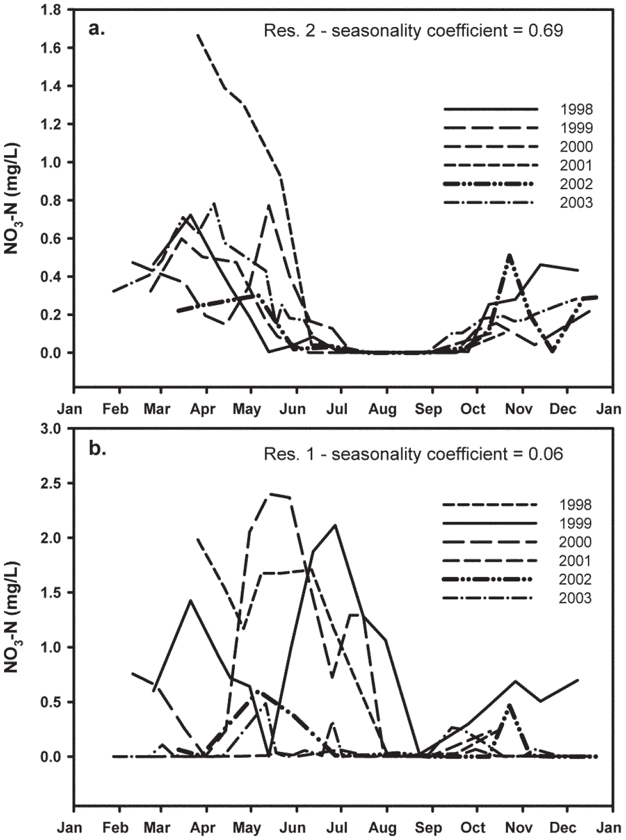

Figure 2.-Annual time series of NO_3-N Reservoirs 1 and 2.

Temporal Coherence

Maximum synchrony among the reservoir pairs ranged from nearly 100% for water temperature to <25% for Chl and SiO_2 (Table 3). Of the chemical parameters, phosphorus fractions (dTP, SRP, TP) and major ions (Mg, alkalinity, Na, K, Cl, Ca) were the most consistently coherent, with r^2 between 43% and 66% averaged across lake-pairs. Time series showed close correspondence in the timing and magnitude of peak concentrations (*e.g.*, Fig. 3a). For this group of variables, the three headwater reservoirs were more synchronous with each other than with Reservoir 3. Of the three headwater impoundments, Reservoir 2 was usually the most synchronous with the downstream reservoir. Grindstone was more closely synchronized with Reservoir 1 than with the other reservoirs for eight of these nine variables (*e.g.*, dTP; Fig. 3a). Reservoir 1 was about equally synchronized with Reservoir 2 and Grindstone. This pattern supports the reasonable expectation that having adjacent watersheds increases the likelihood of co-variation over time.

Dissolved oxygen showed moderate and relatively uniform temporal coherence among reservoir pairs (23-44%). Synchrony for TSS, NVSS, and Secchi depth tended to be greater among the three headwater reservoirs (21-49%) than for pairs that included Reservoir 3 (2-24%). VSS, Chl and SiO_2 had the lowest average temporal coherence with synchrony of most pairings <20%. Timing and magnitude of concentration peaks of these variables were only rarely synchronized among lakes (*e.g.*, Fig. 3b). Algal biomass as indicated by Chl and VSS was least synchronous for pairs including Grindstone ($\leq$15%).

Of the entire group of parameters, synchrony for nitrogen fractions (TN, dTN NO_3-N and NH_4-N), showed the most heterogeneity among lake pairs, with r^2 values usually >3 times greater for combinations of Reservoirs 1, 3 and Grindstone than for pairs that included Reservoir 2. Nitrogen dynamics in Reservoir 2 differed most consistently from the other reservoirs during summer stratification because nitrogen in Reservoir 2 declined faster and reached lower concentrations than the other impoundments (Fig. 2). Nitrogen often exhibited occasional sharp declines in summer in all four

Table 3.-Synchrony (as coefficients of determination) between paired observations for the City of Cameron reservoirs. Values of $r^2 < 0.05$ were not significant ($p>0.05$).

	r^2						
pairs -	**1, 2**	**1, 3**	**1, GR**	**2, 3**	**2, GR**	**3, GR**	**mean**
Temp	0.98	0.98	0.98	0.98	0.99	0.99	0.98
Mg	0.76	0.51	0.75	0.73	0.65	0.53	0.66
Alk	0.70	0.56	0.71	0.54	0.74	0.54	0.63
dTP	0.66	0.61	0.70	0.66	0.56	0.47	0.61
Na	0.79	0.37	0.78	0.57	0.71	0.36	0.60
TP	0.67	0.63	0.57	0.48	0.54	0.36	0.54
K	0.64	0.47	0.64	0.71	0.39	0.37	0.54
Cl	0.73	0.20	0.75	0.53	0.64	0.21	0.51
SRP	0.35	0.60	0.67	0.43	0.38	0.46	0.48
Ca	0.59	0.30	0.57	0.37	0.49	0.25	0.43
TN	0.15	0.63	0.65	0.11	0.13	0.47	0.36
D.O.	0.29	0.44	0.36	0.44	0.25	0.23	0.34
dTN	0.07	0.67	0.63	0.13	0.04	0.48	0.34
NVSS[1]	0.41	0.24	0.37	0.06	0.36	0.07	0.25
NO_3-N	0.10	0.39	0.42	0.06	0.21	0.29	0.24
TSS[1]	0.49	0.21	0.29	0.15	0.21	0.02	0.23
NH_4-N	0.03	0.40	0.44	0.02	0.05	0.27	0.20
Secchi	0.30	0.11	0.32	0.04	0.27	0.02	0.18
VSS[1]	0.30	0.29	0.09	0.25	0.01	0.01	0.16
Chl	0.16	0.22	0.15	0.17	0.00	0.06	0.13
SiO_2	0.08	0.20	0.12	0.16	0.07	0.00	0.11

[1] Outlying data for Reservoir 2 for 6 April 2003 omitted. Their inclusion reduces r^2 for pairs including 2 by more than half.

reservoirs, but declines were sometimes reversed by inflow or mixing events in reservoirs 1, 3 and Grindstone (*e.g.*, Fig. 2b.). In Reservoir 2, nitrogen concentrations remained low (dTN <0.5 mg/L, NO_3-N <0.05 mg/L) until fall overturn in all six years of the study (Fig. 2a). Several rainfall events that influenced all the reservoirs left the major N-fractions unaffected in Reservoir 2 despite large effects on phosphorus fractions and major ions. This result suggests inflows to Reservoir 2 during summer had lower N-concentration than inflows to the other lakes.

Another interesting feature of nitrogen data is that high coherence of N dynamics among reservoirs 1, 3 and Grindstone contrasts with their seasonality (Table 2). Excepting NH_4-N, N fractions were strongly seasonal (56-63%) in Grindstone where NO_3-N was always present in spring and usually >0.5 mg/L. In reservoirs 1 and 3, NO_3-N in spring was highly variable (*e.g.*, Fig. 2), and in some years temporarily fell below detection, thus yielding no consistent seasonal pattern in NO_3-N, TN or dTN. Coherence of N dynamics among these three lakes owes to the dominating effect of inflow events that punctuated their time series and, in Grindstone, were superimposed on an underlying seasonal pattern.

Discussion

The City of Cameron reservoirs comprise a suite of lakes near the upper end of the trophic continuum for Missouri reservoirs. Among the 137 reservoirs for which we have extensive data, Grindstone and Reservoir 1 have the highest and second highest mean summer (May-August) TN, the second and forth highest mean summer TP and the seventh and third highest mean summer Chl (Jones and Knowlton 2005b), respectively. Cropland, used principally for cultivation of heavily fertilized corn and soy beans, makes up approximately half of both catchments and is likely the principle source of nutrients to these waterbodies (Jones *et al.* 2004). Also, both reservoirs have hydrologic flushing rates ≥3.3/year, which is in the upper 20% for reservoirs in the Prairie Ecological

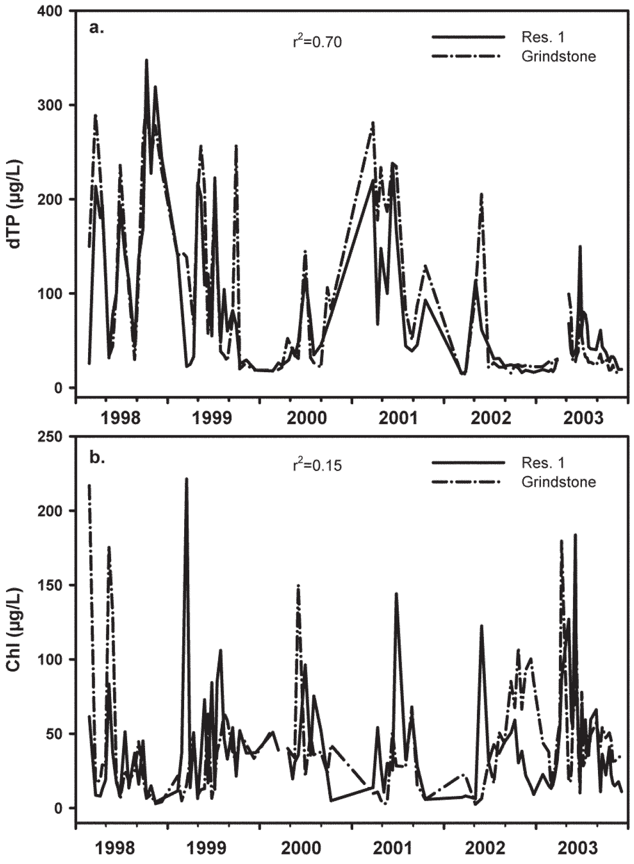

Figure 3.-Time series of dTP and Chl in Reservoir 1 and Grindstone 1998-2003.

Division of the state. Among artificial lakes in the agricultural prairie regions of Missouri and southern Iowa, flushing rate is a strong correlate of mean nutrient concentrations (Jones *et al.* in prep). Reservoir 2 is in the upper third of Missouri reservoirs for TP, TN and Chl, but lags well behind its neighbors. Both the proportion of cropland in its catchment and its flushing rate are less than half those of Reservoir 1 and Grindstone. Reservoir 3 has the fifth highest mean summer Chl among Missouri reservoirs and is in the upper 10% for TP and TN. Catchment land use and flushing rate for Reservoir 3 cannot be quantified to parallel measurements for the other Cameron reservoirs because a large portion of its inflow comes from outside its topographic catchment (pumped from Grindstone). Also, the fact that most of its water income (~80%) is released or pumped from other reservoirs suggests that water quality in the source reservoirs might be a more immediate determinate of trophic state than land use in the catchment. The intermediate position of Reservoir 3 in the trophic rankings among the four impoundments is consistent with that proposition.

The assumption that some internal lake conditions are controlled by external influences is strongly supported by the degree of temporal coherence among the City of Cameron reservoirs. For example, the fact that Mg showed high coherence (>50%) among all pairings of the Cameron reservoirs attests to the uniformity of physical and hydrologic conditions in this compact study area and uniformity of edaphic conditions with respect to Mg. For conservative ions such as Mg, as well as Na and Cl, it is safe to assume that temporal variation is driven almost entirely by either evaporation or mixing of new inflows of concentrations higher or lower than those currently found in the water body. A high level of synchrony between two lakes suggests uniformity in external conditions such as temperature, humidity, wind, insolation, and inflow plus uniformity of edaphic conditions in the catchment, both natural and anthropogenic, that control yield and export of the material in question. The relatively low synchrony for Na and Cl for Reservoir 3 paired with Reservoir 1 and Grindstone is thus likely more attributable to differences in the features of their catchments controlling the timing of the availability of Na and Cl for export, than differences in physical or hydrologic dynamics.

Compared with the other reservoirs, Reservoir 3 is hydrologically distinct in that much of its watershed (70%) is impounded, and the majority of its inflows are released from upstream lakes or pumped from Grindstone. Given these differences, Reservoir 3 exhibited a surprisingly high degree of temporal coherence with the other reservoirs (Table 3). But controlled releases or pumping from the other lakes produces only gradual changes in Reservoir 3. Inflows from the unimpounded portion of its watershed and overflow during large precipitation events from upstream lakes seem to drive the temporal dynamics of Reservoir 3. The resulting coherence data show no greater contrast between Reservoir 3 and the three headwater reservoirs than might be expected from the positions of their watersheds.

In comparison with conservative ions, variables such as dTP and SRP are nonconservative and susceptible to biological uptake. For these phosphorus fractions to exhibit such high coherence (35-70%) among the four reservoirs requires uniformity not only in external physical, hydrological and edaphic conditions, but also a similarity in the biological response to changing phosphorus concentrations. In these productive reservoirs, a uniformly strong biological demand for soluble phosphorus appears to result in similarly rapid declines in new inputs of phosphorus in all four impoundments (Fig. 3a). This explanation also seems true for nitrogen fractions, even though coherence was less uniform for nitrogen because of divergent nitrogen dynamics in Reservoir 2 related to edaphic or land use conditions. Differences in fertilization and cropping practices among the four catchments might account for this divergence in nitrogen. Overall, however, dynamics of phosphorus and nitrogen in these lakes do not suggest that their eutrophic state resulted in a diminished influence of external inputs on nutrients as we had originally hypothesized.

Given that several variables in each of the reservoir-pairings exhibited >50% temporal coherence, the lack of synchrony for some variables is likely due to heterogeneity of either edaphic conditions in the catchments or purely internal dynamics. We have no means of definitively separating these two sources of divergence, but the data provide basis for reasonable speculation. Silica, for example, is a biologically active substance sometimes depleted to undetectable concentrations in all four reservoirs. As with SRP, time series of SiO_2 were typified by spikes related to inflows and often by rapid declines from biological uptake. But silica was much less temporally coherent among the reservoirs than was SRP because post-spike declines were less frequent and predictable than dissolved phosphorus. Demand for SiO_2 is restricted mostly to the immediate growth needs of siliceous microorganisms, but SRP is used by virtually all algae and bacteria and many algae store far more phosphorus than required for their immediate needs (Wetzel 2001). Thus silica dynamics are tied more closely to the taxonomic composition of the microbial community than universal nutrients such as phosphorus and nitrogen. We lack data on the coherence of the reservoir phytoplankton communities, but indices of total biomass (Chl and VSS) demonstrated little coherence among these impoundments (Fig. 3b). Internal biological dynamics seem likely to restrict the temporal coherence of SiO_2 in lakes.

Transparency is a key water quality variable often subject to biological control (Carlson 1977). But in the Cameron reservoirs, as in many Missouri impoundments, Secchi is controlled mostly by mineral seston (Jones and Knowlton 1993). In all four reservoirs, minimum transparency was associated with turbid conditions characterized by low Chl and elevated concentrations of NVSS which was the dominant fraction of TSS (Table 1). NVSS was moderately coherent (36-41%) among the three headwater reservoirs, and Secchi depth gave parallel results (27-32%). NVSS and Secchi measurements for Reservoir 3, however, did not track the other lakes, perhaps because artificial circulation disrupted the usual processes by which wind and stratification control the settling and resuspension of suspended sediment. In other respects, stratification patterns had no obvious effect on our results despite the continuum of stratification from holomixis in Reservoir 3 to stable summer stratification in Reservoir 2. Strong stratification in Reservoir 2 did not seem to isolate the surface layer from the effects of new inflows as occurs in larger, deeper reservoirs (Knowlton and Jones 1989, Knowlton and Jones 1995).

Chl and VSS showed very little coherence among these impoundments, despite proximity, similarity of morphology and trophic state, and the relatively coherent behavior of major nutrients. Lack of temporal coherence does not prove the absence of external influences on the dynamics of algal biomass in these reservoirs, but suggests that either internal controls are dominant, or that the individual waterbodies have a high degree of individuality in their responses to whatever external influences might be in force (Baines *et al.* 2000). In either instance, lack of synchrony for biomass indices is not surprising. If we assume that the balance between growth and loss processes that determines the biomass of phytoplankton at a given time is sensitive to variables such as dissolved nutrient concentrations, mixed-layer irradiance and water column stability (Reynolds 1997), it is difficult to envision how the complex combination of these many variables could vary synchronously among different lakes even if some of the individual variables were temporally coherent.

Algal biomass is more likely to be temporally coherent among lakes with distinct seasonal patterns (Marshall and Peters 1989, Kasprzak *et al.* 2000). In north temperate lakes with prolonged ice cover, algal biomass in winter is usually much less than in the growing season, and many such lakes show distinct spring and/or autumn biomass peaks. Winter is underrepresented our data set, which may contribute to the lack of seasonality observed for Chl and VSS (Table 2). Conversely, in other shallow lakes in Missouri, Chl concentrations are not predictably less in winter than other seasons. Year-round measurements from Lake Woodrail (Jones and Knowlton 2005b), a dozen floodplain lakes (Knowlton and Jones 1997), and shallow uplake areas in Mark Twain Lake (Knowlton and Jones 1995) show Chl peaks occurring throughout the year with no indication recurrent spring or autumn blooms.

A comparison of synchrony of water quality variables displayed by the City of Cameron reservoirs to other lake groups cannot be easily evaluated. Most investigations of temporal coherence of lakes have used annual or seasonal means rather than synoptic observations and involve lakes spanning wide geographic areas (Magnuson *et al.* 1990, Baines *et al.* 2000, George *et al.* 2000, Fölster *et al.* 2005). Two studies, however, provide comparable data. Using a 2.5-year series of matched observations from two Texas reservoirs, Chrzanowski and Grover (2005) found relatively low synchrony ($r^2 <$ 18%) for nitrogen and phosphorus fractions, Secchi, and Chl. Among the 21 variables compared, only silica (r^2=55%) and water temperature (r^2=94%) exhibited >35% synchrony. The reservoirs compared were much larger (>3600 ha) and more distant (55 km apart) than the City of Cameron reservoirs, and as much as 14 days separated their matched samples, factors that may have contributed to the relative lack of coherence. Kasprzak *et al.* (2000) observed generally greater synchrony in matched samples (usually collected the same day) from two small (10-12 ha) German seepage lakes less than 2 km apart. Evaluated separately for the two years of the study, coherence for TP and TN ranged from 37-61% in epilimnetic samples and 37-86% in the hypolimnion. Coherence of Chl was 18-45%, and coherence of other biological variables (biomass of phytoplankton and selected zooplankton taxa) ranged up to 83%. In general, the potential for coherence will be greatest among similar water bodies in close proximity as with the City of Cameron reservoirs.

Management of water quality often involves exerting human control over predictable, external influences that govern factors such as nutrient concentrations, transparency and algal biomass in lakes. Temporal coherence implies existence of external governing factors that operate similarly across lakes in a region. Temporal coherence may thus be an indication of the potential for management control. If so, results from the Cameron reservoirs suggest a much greater potential for controlling nutrients than either transparency or, especially, algal biomass. This conclusion, while based on overly broad assumptions, may be correct for turbid, eutrophic reservoirs like many of those found in the prairie regions of Missouri, Iowa and neighboring states. In such impoundments, nitrogen and phosphorus may frequently exceed algal needs with the result that reducing nutrient inputs may not yield proportional reductions of biomass (Reynolds 1997). Also, transparency in these lakes is typically controlled by mineral turbidity rather than phytoplankton (Jones and Knowlton 1993), meaning that control of biomass and transparency may be distinct undertakings. To the extent that suspended sediment concentrations are related to catchment features and land use, transparency may be more amenable to management controls than algal biomass.

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