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Suspended solids in Missouri reservoirs in relation to catchment features and internal processes

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Abstract

Mean total suspended solids (TSS), in 135 Missouri reservoirs range from 1.2 to 47 mg/l. The volatile (VSS) and non-volatile (NVSS) fractions range from 0.6 to 9.6 mg/l and 0.5 to 37 mg/l, respectively. %NVSS is the larger fraction and declines through summer as %VSS increases. Suspended solids (particularly VSS) correlate with metrics of lake trophic state and are positively related with the proportion of cropland (%C, $r = 0.69-0.74$) in their catchments, negatively related with forest cover ($r = -0.54$ to -0.56), and weakly related with grassland ($r<0.31$). Regressions including %C with dam height (representing morphometry) and flushing rate (representing hydrology), explain ~70% of cross-system variation in TSS and 67% in VSS. Dam height and %C explain 57% of variation in NVSS. Residual analysis shows statewide models under-predict suspended solids in urban reservoirs. Effects of catchment features on summer TSS largely reflect internal plankton growth mediated by influent nutrients (affecting VSS) over direct sediment input (affecting NVSS).

Keywords: Suspended solids; Land cover; Reservoirs; Nutrients; Chlorophyll; Seston

1. Introduction

Strong influences of the geographic setting on the chemical and biological characteristics of streams and lakes are long recognized and widely accepted (Rawson, 1939; Hynes, 1975; Duarte and Kalff, 1989), as are the modifying roles of morphology and hydrology (Rawson, 1955; Edmondson, 1961; Vollenweider, 1975). Reservoirs are constructed in river valleys with large catchment areas and short water residence time relative to natural lakes (Kalff, 2002); so it follows that water quality in these artificial lakes directly reflects both the physiography and human alteration of their drainage basins (Jones and Bachmann, 1978; Canfield and Bachmann, 1981). Consistent with theory, Jones et al. (2004) showed that for 126 Missouri reservoirs, the proportion of cropland cover in their catchments (a surrogate for nutrient loss from agriculture), along with dam height (a morphology surrogate) and an index of hydrologic flushing, accounted for ~77% of the among-system variation in total phosphorus (TP) and total nitrogen (TN) concentrations. This empirical analysis supports limnological theory that nutrient concentrations in lentic systems are largely determined by external inputs as modified by morphology and hydrology. Similar relations have been quantified among lakes and reservoirs in other regions (Field et al., 1996; Knoll et al., 2003).

Total suspended solids (TSS) and its volatile (VSS) and non-volatile fractions (NVSS) are positively

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correlated with TP in Missouri reservoirs (Hoyer and Jones, 1983; Jones and Knowlton, 1993). Earlier studies show suspended solids in Missouri streams are positively correlated with row crop agriculture and negatively correlated with forest cover (Perkins et al., 1998) which indicates catchment cover-type would directly influence delivery of suspended solids to downstream reservoirs. Presumably, particulate materials in reservoirs are related to catchment features. Allochthonous suspended solids of fluvial origin, largely measured as NVSS, are an important component of reservoir seston (Canfield and Bachmann, 1981; Jones and Knowlton, 1993; Knowlton and Jones, 1995). Whereas organic seston, measured as VSS, would partly result from autochthonous production and would reflect catchment features controlling algal production mediated by nutrient input and water residence time. Thus, both fractions of reservoir suspended solids are potentially regulated by catchment features.

In this paper we extend our analysis of reservoir nutrient–watershed relationships to explore among-reservoir variation in TSS and its two fractions. We use multiple regression models to demonstrate the influence of land use, basin morphology, and hydrology on TSS, VSS, and NVSS. We also explore the phenology of suspended solids and its composition in relation to nutrients and algal biomass in an attempt to assess the relative importance of allochthonous versus autochthonous sources.

2. Materials and methods

Data used in this analysis come from 135 Missouri reservoirs that were sampled from the surface layer near the dam seasonally on three or four occasions during May–August in 1979–2003 (Jones and Knowlton, 1993; Jones et al., 2004). Individual reservoirs were sampled from 4 to 21 summer seasons and most reservoirs were represented by data from ≥ 9 seasons. Samples were processed for chlorophyll (Chl), TP, TN and Secchi depth by standard methodology (Knowlton and Jones, 1995). TSS were determined by filtering a known volume of lake water through Whatman 934-AH filters that were pre-rinsed, dried (105 °C), ashed (550 °C), and tared (American Public Health Association (APHA), 1985). NVSS were determined by weight after ashing TSS samples, and VSS were determined by difference (TSS−NVSS). Percent composition of TSS was expressed as %NVSS and %VSS and logit-transformed for statistical analysis.

Analyses are based on lake mean values which were nested averages determined by calculating the geometric mean (ln-transformed) for each summer and then calculating the geometric mean across all summers. Morphometric variables and cover-type within the watersheds (Table 1) have been described by Jones et al. (2004). Cover-type categories are expressed as a proportion of the watershed area. Median values of the major cover-types were 31% grass/pasture (%G), 24% forest (%F), 13% cropland (%C) and <1% urban area (%U) but individual proportions ranged from 0% to >74% in each cover-type. Collectively, >85% of the land area in most (80%) basins was forest, cropland and grass, the remaining area was classified as water (median 5%) or urban. Some 80% of the catchments had <5% urban area. However, nine reservoirs within metropolitan Kansas City had 52–96% urban area (mostly residential) and this sub-set is treated separately in the land cover analysis. An index of hydrologic flushing rate (1/y) was estimated for each reservoir by multiplying mean annual runoff (Missouri Deparatment of Natural Resources, 1986) by watershed area and dividing by reservoir volume.

Relationships between landscape variables and suspended solids were examined by least squares methods of single and stepwise multiple regression. Cover-type (%) was transformed using logit (adding 0.003 to avoid zero values). Unless otherwise stated, all correlation and regression analyses were based on ln-transformed lake means and logit-transformed values of cover-type and % composition. Statements of statistical significance imply $P<0.05$.

Table 1
Means, medians and ranges of land cover, dam height, flushing rate and suspended solids data for 135 Missouri reservoirs

	Mean	Median	Minimum	Maximum
%Cropland	19.5	13.3	0	73.7
%Grassland	32.1	30.6	0	77.9
%Forest	34.8	24.0	0	95.2
%Urban	7.2	0	0	96.4
Dam height (m)	16.2	14.3	4.6	76.8
Flushing rate (1/y)	4.8	1.2	0.1	142.2
TSS (mg/l)	7.6	6.6	1.2	47.0
VSS (mg/l)	3.1	2.9	0.6	9.6
NVSS (mg/l)	4.1	3.1	0.5	37.0
%NVSS	52.3	53.0	25.5	84.2

3. Results

3.1. Suspended solids

In these Missouri reservoirs mean TSS ranged from 1.2 to 47.0 mg/l with mean and median values of 7.6 and 6.6 mg/l, respectively (Table 1, $n = 135$). Mean TSS was <13 mg/l in >90% of the reservoirs and only two water bodies had mean TSS > 25 mg/l. In about half the reservoirs TSS averaged between 4 and 9 mg/l. Among ln-transformed reservoir means (Table 1, Fig. 1), TSS was positively correlated with TP, TN and Chl ($r = 0.84-0.94$) and negatively correlated with Secchi (−0.97).

NVSS ranged between 0.5 and 37.0 mg/l with a mean and median of 4.1 and 3.1 mg/l, respectively (Table 1) and VSS ranged between 0.6 and 9.6 mg/l with a mean and median of 3.1 and 2.9 mg/l, respectively (Table 1). Across reservoir systems these two fractions were correlated (Fig. 2, $r = 0.71$) but NVSS was more variable than VSS (coefficient of variation = 118% versus 58%). TSS was more strongly correlated to NVSS ($r = 0.94$) than to VSS ($r = 0.90$). Correlations between VSS and TP, TN, and Chl ($r = 0.92$, 0.86 and 0.97, respectively) were stronger than with NVSS ($r = 0.83$, 0.73, and 0.64, respectively). Both fractions were negatively correlated with Secchi ($r = -0.93$ for NVSS and −0.86 for VSS).

Seasonally, TSS and NVSS tended to decline over summer (Fig. 3a). Individual observations expressed as a proportion of their seasonal means were negatively correlated with day-of-the-year ($r = -0.2$ and −0.38, respectively, $n = 5023$, untransformed data). VSS, in contrast tended to increase over summer ($r = 0.13$, $n = 5023$, untransformed data, Fig. 3b). Seasonal maximum NVSS was often observed in the first seasonal sample collected in a given reservoir (49% of 1433 seasonal data sets) but rarely in the last seasonal sample (18% of seasonal data sets). Whereas maximum VSS was often the last sample of the season (38% of seasonal data sets).

On average NVSS was a slightly larger fraction of TSS than VSS (mean ~52% versus 48%, Table 1). In about 60% of the reservoirs %NVSS was larger than %VSS, but in about half of the water bodies the two proportions were within ±15% of one another (Fig. 2). Among reservoirs %NVSS increased with NVSS ($r = 0.67$) and TSS ($r = 0.39$). As the compliment of %NVSS, %VSS showed equal correlations in the opposite direction. Neither %NVSS or %VSS was significantly correlated to VSS or Chl. Among individual (unaveraged) observations %NVSS was significantly seasonal showing a negative correlation to day-of-the-year ($r = -0.27$, $n = 5024$, untransformed data, Fig. 3c). On average, %NVSS declined from about 63% in mid-May to 45% in mid-August with %VSS showing the complimentary trend.

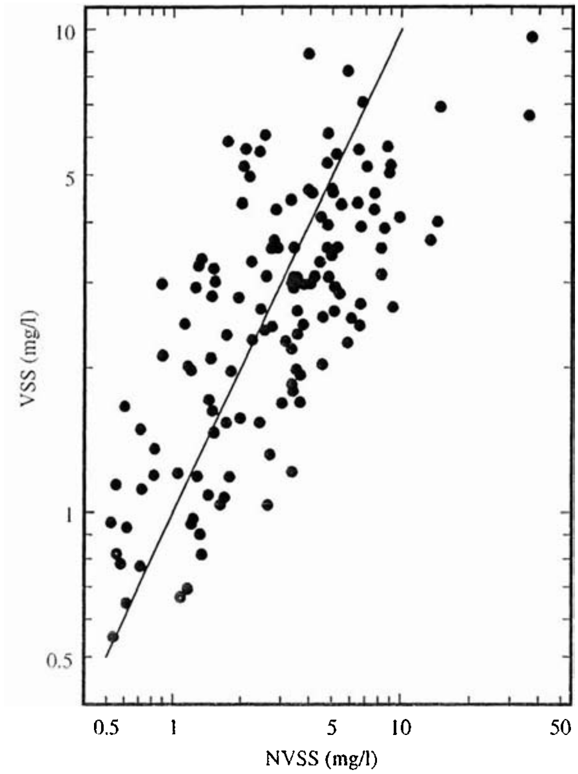

Fig. 2. Relation of mean VSS to mean NVSS from 135 Missouri reservoirs. The solid line marks a 1:1 ratio of concentrations.

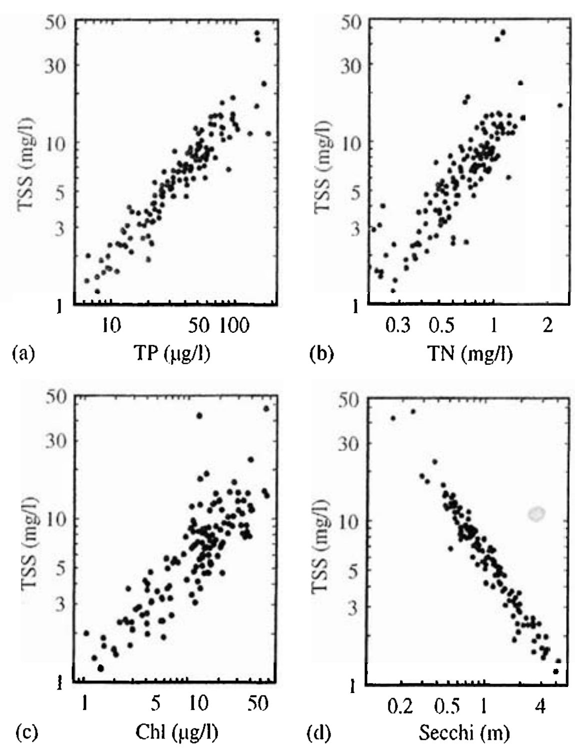

Fig. 1. Relation of mean TSS to (a) mean TP ($r = 0.94$), (b) mean TN ($r = 0.85$), (c) mean Chl ($r = 0.84$) and (d) mean Secchi depth ($r = -0.97$) for 135 Missouri reservoirs.

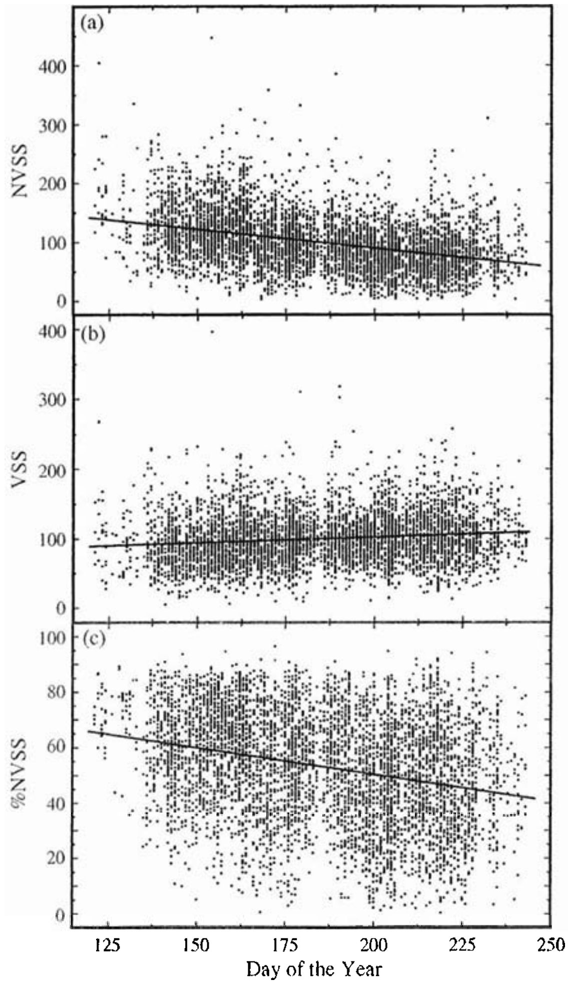

Fig. 3. Relation to day of the year of (a) NVSS ($r = -0.38$), (b) VSS ($r = 0.13$) and (c) %NVSS ($r = -0.27$). NVSS and VSS values are plotted as a percent of their seasonal means ($n = 1433$ seasonal data sets). Trend lines were fitted by least squares.

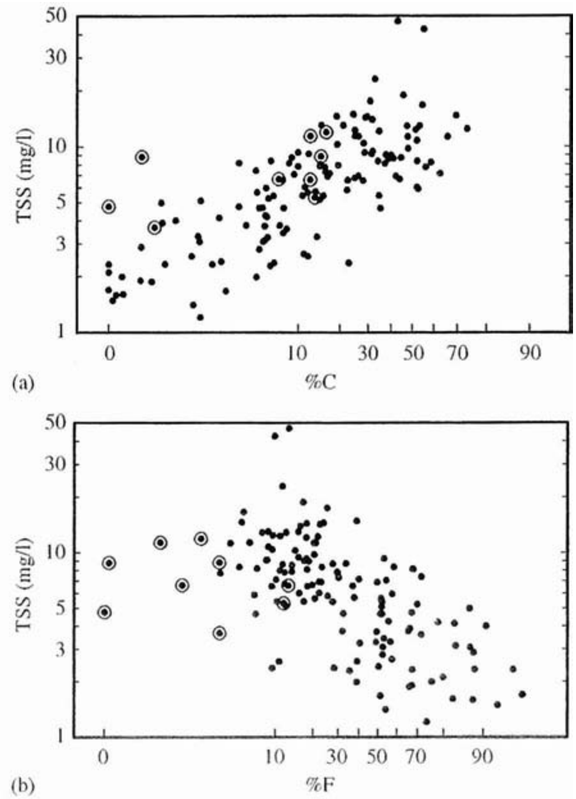

Fig. 4. Mean TSS for Missouri reservoirs versus percent cover of (a) cropland (%C, $r = 0.74$) and (b) forest (%F, $r = -0.59$) in reservoir catchments. Circled observations are for water bodies with catchments including >50% urban cover.

3.2. Relations with land cover, morphology and hydrology

TSS and both fractions were positively related with %C ($r = 0.69-0.74$) and negatively related to %F ($r = -0.54$ to -0.59) within their watersheds (Fig. 4, $n = 135$). Percent grassland (%G) showed a weak ($r<0.31$) positive relation with VSS and TSS, but was significant for NVSS ($r = 0.22$) only if the nine urban reservoirs (%U >50%) were excluded from the analysis. Multiple regression, excluding the urban reservoirs, showed that with %C inclusion of dam height (a surrogate for morphometry) and the flushing index explained ~70% of the variation in TSS and 67% of the variation in VSS (Table 2). Only dam height entered with %C to explain 57% of the variation in NVSS. Residual variance in these regressions was not appreciably reduced by addition other land cover categories or a quadratic term for %C, and relations were weaker when %F was used rather than %C. Only two reservoirs had mean TSS > 25 mg/l (Fig. 4). Excluding these water bodies from the analysis caused no large (>9%) changes in any regression coefficient except, with their removal, the effect of flushing rate on TSS was not significant at the 5% level ($p = 0.08$).

TSS composition was significantly related to land cover with %NVSS increasing slightly with %C ($r = 0.28$) and %VSS showing the opposite trend. Multiple regressions showed a slight positive influence of %C on %NVSS and a negative influence of %G, but jointly the two variables only accounted for 13.5% of the variation in TSS composition. None of the other independent variables tested contributed significantly to the model.

Suspended solids in the nine reservoirs with %U >50% were consistently under-predicted by the state-wide regression models. Residuals (observed minus predicted from models in Table 2) were mostly positive and were significantly correlated ($r = 0.7-0.95$) with the

Table 2
Multiple regression models of the effect of land cover, lake morphometry and hydrology on suspended solids for 126 non-urban Missouri reservoirs. Regression coefficients are for ln-transformed data except %cropland, %grassland and %NVSS which were logit transformed

Dependent variables	Independent variables				Intercept	r^2	RMSE[a]
	%Cropland	Dam height (m)	Flushing rate (1/y)	%Grassland			
TSS (mg/l)	0.316	−0.345	0.064	n.s.	3.293	0.698	0.392
VSS (mg/l)	0.262	−0.406	0.070	n.s.	2.503	0.665	0.376
NVSS (mg/l)	0.355	−0.323	n.s.	n.s.	2.579	0.570	0.568
%NVSS	0.139	n.s.	n.s.	−0.164	0.230	0.135	0.561

[a]Root mean-squared error.

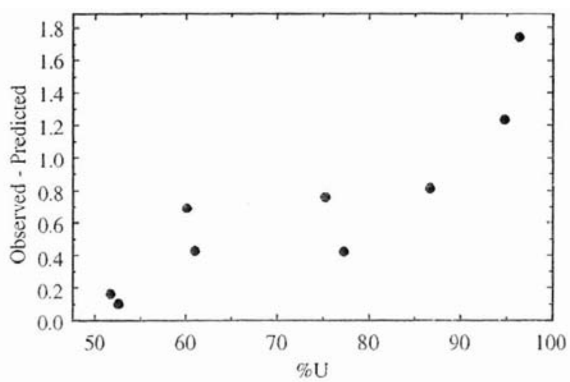

Fig. 5. Residuals from the statewide TSS regression in Table 2 in relation to percent urban cover for nine reservoirs with %U >50% ($r = 0.88$).

proportion of urban cover (Fig. 5). As expected, these residuals suggest reservoirs with urban watersheds have larger values of suspended solids than those with forest and grass cover (non-cropland).

4. Discussion

TSS concentrations in lakes have received relatively little attention in limnological literature compared to algal biomass and other components of organic seston, but a sampling of available literature shows values range over about three orders of magnitude, from less than 0.1 mg/l (e.g. Morris et al., 1995) to >100 mg/l (Gerbeaux and Ward, 1988; Lindström et al., 1999; Hatch, 2003; Roozen et al., 2003). TSS is a positive correlate of TP (Lindström et al., 1999) and generally reflects lake trophic state (Howard-Williams and Vincent, 1984). For example, among data from 65 mostly oligotrophic lakes (median Chl = 0.9 μg/l) in the US and Argentina presented by Morris et al. (1995), the median TSS was only 1.0 mg/l (range 0.02–9.17 mg/l) compared to a median of 7.3 mg/l (range 0.2–127.2) observed by Nõges et al. (2003) in data from 86 shallow, mostly eutrophic (median Chl = 16.4 μg/l) European lakes, and a median of 22 mg/l (range 5–64 mg/l) found among 15 shallow, hypereutrophic (median Chl = 78 μg/l) Danish lakes by Jeppesen et al. (2003). Notable exceptions to the TSS-trophic state trend are lakes of low productivity and high inorganic turbidity such as Lake Tekapo, New Zealand (Chl = 0.74 μg/l, TSS = 21 mg/l—Rae et al., 2001) and Tuttle Creek Reservoir, Kansas. Tuttle Creek has extremely low primary productivity (Marzolf and Osborne, 1972) and TSS frequently exceeds 100 mg/l (Arruda et al., 1983). In Missouri reservoirs, a combination of high TSS and low Chl is sometimes observed after flood inflows, but is not a chronic condition in our data set. Among Missouri reservoirs, TSS is a close correlate of Chl ($r = 0.84$). The median value from Missouri reservoirs (6.6 mg/l) is probably typical of moderately productive water bodies around the world. Regionally, Missouri reservoirs rank well below their more eutrophic counterparts in neighboring Iowa (median TSS = 16.8, $n = 77$ reservoirs—Hatch, 2003).

NVSS is reported less frequently than TSS, but the proportion of non-volatile seston seems to range from lows of approximately 20% when seston is dominated by phytoplankton to ~90% in water dominated by terrestrial or resuspended tripton. In Iowa water bodies (Hatch, 2003), %NVSS averaged 51% in reservoirs compared to 41% in glacial lakes and 21% in hypereutrophic (mean Chl = 78 μg/l) Corn Belt lakes in southern Minnesota. In the 17 hypereutrophic Danish lakes studied by Jeppesen et al. (2003), NVSS averaged 26% of TSS compared to a mean of 51% NVSS reported by Effler et al. (2001) for nine New York reservoir basins (range 26–92%). High proportions of NVSS are indicative of allochthonous or resuspended sediment, but calcite precipitation (whitings) in hard-water lakes and internal production of diatom frustules undoubtedly contribute substantially to NVSS in some instances. We lack compositional data on NVSS for Missouri reservoirs, but clay minerals are an obvious component of most samples with high NVSS values. It seems %NVSS is a reasonable index of the presence of allochthonous or resuspended tripton.

In Missouri streams, NVSS is usually the dominant fraction of TSS and %NVSS is typically >80% in our stream data sets (e.g. Perkins and Jones, 1994; Perkins et al., 1998). Among these Missouri streams TSS is positively correlated to %C (Perkins et al., 1998), presumably because of increased erosion and runoff associated with agriculture, which represents the most pervasive disturbance in most Missouri watersheds. On this basis we expected the relation between watershed features and reservoir TSS to reflect the direct influence of NVSS input from streams connecting reservoirs to their catchments. Under this scenario, NVSS would be the stronger correlate of catchment land use because VSS is a surrogate of algal biomass (Jones and Hoyer, 1982). As such, the effect of catchment features on VSS would operate indirectly through nutrient inputs and would be less distinct than the direct land-to-stream-to-reservoir transport of NVSS. Nonetheless, our analysis shows the opposite—a stronger influence of catchment and hydrology on VSS (Table 2). Certain features of Missouri reservoirs and our data probably contribute to these unexpected results.

Most Missouri reservoirs strongly stratify in summer, a condition that substantially buffers the downlake (near the dam) epilimnion from the influence of new inflows. Inflows are most influential downlake before summer stratification is fully established and in riverine headwater areas not represented by our downlake sampling sites. Spring floods commonly produce turbid, high-NVSS conditions downlake in Missouri reservoirs but similar events in mid to late-summer typically enter as interflows without direct influence on surface waters near the dam (Knowlton and Jones, 1995). The seasonality of NVSS inputs probably underlies the trend of NVSS decline during summer (Fig. 3). In a year-long study of 15 northern Missouri reservoirs (University of Missouri, unpublished data) %NVSS declined, on average, from 78% in spring to 35% in late summer, with a mean decline of 43% in NVSS during this period. Because our data come from downlake reaches of these impoundments they represent conditions after in-reservoir processes have altered inflow (Jones and Knowlton, 1993). Such factors mute the influence of catchment features on mean NVSS in summer but available data suggest the signal would be stronger prior to stratification.

In contrast, the correlation between VSS and TP is so strong ($r = 0.92$) that factors affecting one, assuredly influence the other (Lindström et al., 1999). In multiple regression, Jones et al. (2004) found %C, dam height and flushing rate to account for 77% of variation in mean TP, and the same variables here account for 67% of variation in mean VSS (Table 2). Phosphorus accounts for most variation in average algal Chl among Missouri reservoirs (Jones and Knowlton, 1993; Jones and Knowlton, in press) and the correlation between VSS and Chl ($r = 0.97$) suggests they are fundamentally interchangeable as indices of algal biomass (Jones and Hoyer, 1982). Thus, the strongest influence of catchment features on TSS in Missouri reservoirs during summer is mediated through the control of algal growth by nutrients.

Concentrations and composition of suspended material in lakes reflects a complex and dynamic balance among fluvial inputs, autochthonous production, resuspension, washout, mineralization and settling (Lindström et al., 1999; Malmaeus and Håkanson, 2003). Elements of several of these phenomena are evident in this analysis, but the coarse scale of the data limits our ability to quantify specific contributions of the contributing processes. Our current results provide a means of predicting long-term average concentrations of TSS, VSS and NVSS in Missouri reservoirs during summer based on catchment features, morphology and hydrology. Extending these results to other regions and lake-types and resolving the temporal variability of TSS in individual lakes (Malmaeus and Håkanson, 2003) will require additional study.

5. Conclusions

In summary, TSS in Missouri reservoirs generally includes a large fraction of mineral seston presumably derived from terrigenous sources either directly or by resuspension of previously deposited material. TSS, especially the autochthonous VSS fraction, is strongly correlated to indicators of lake trophic state including algal biomass, nutrient concentrations and lake depth. Both fractions of TSS are correlated to watershed disturbance as indicated by %C, but the mechanisms of these effects probably differ. Quantifying the functional connections between reservoir seston and catchment features will require additional study.

Acknowledgments

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