Role of land cover and hydrology in determining nutrients in mid-continent reservoirs: implications for nutrient criteria and management

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Abstract

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Effects of nutrient input, hydraulic flushing rate and depth on reservoir nutrients were examined in the mid-continent landscape of the Ozark Highlands and Plains in Missouri and Plains of southern Iowa. Regionally the clear south-to-north increase in reservoir nutrients, amounting to a 4-fold increase in median total phosphorus (TP) and 3-fold increase in median total nitrogen (TN), showed a strong cross-system pattern with cropland cover (a surrogate for nonpoint-source nutrient loss from agricultural watersheds) but not with an index of hydraulic flushing rate. Cropland accounted for variation in TP in the Ozarks (51%) and TN in all 3 regions (Ozarks 58%, Plains 41%, Iowa 27%). Flushing accounted for variation in TP in the Missouri Plains (49%) and Iowa (29%). Our models suggest large-scale nutrient reduction will require massive changes in land cover to reduce nutrient input. In the Missouri Plains, for example, reducing cropland from 60% to 30% reduces TP and TN by only about 20% when other factors are held constant. Hydrology places added limits on reducing reservoir nutrients; consistent with theory, TP values in Missouri Plains reservoirs effectively double between flushing rates of 0.25 and 2 at any given cropland value. Dramatic nutrient reduction in these reservoirs is unlikely, and the influential role of hydraulic flushing adds additional management challenges for compliance with regional nutrient criteria. The analyses suggest hydrology must be considered when setting nutrient criteria, and it would be unreasonable to establish criteria based on water bodies with long retention time and apply them to rapidly flushed lakes.

Key words: flushing rate, hydrology, nutrient criteria, reservoirs, watersheds

A central concept of applied limnology is that lake phosphorus concentrations (TP) increase as a direct function of nutrient loading which, in turn, is modified by hydraulic retention time and sedimentation (Edmondson 1961, Vollenweider 1975, Welch and Jacoby 2004). Across the continuum of possible combinations of these deterministic variables, TP will be greatest among lakes with high inflow concentrations, low sedimentation, and rapid hydraulic flushing (Welch and Jacoby 2004). To reverse water quality problems associated with eutrophication, lake management typically focuses on reducing external nutrient loading (Sas 1989, Welch and Jacoby 2004, Cooke *et al.* 2005) because little can be done to manipulate natural sedimentation rates, and altering the hydrology of individual water bodies may be impractical or impossible.

Empirical evidence suggests phosphorus sedimentation and hydraulic flushing rates are positively correlated (Larsen and Mercer 1976, Vollenweider 1976, Canfield and Bachmann 1981). In steady-state formulations hydraulic flushing has greater influence on in-lake TP than sedimentation (Welch and Jacoby 2004), thereby allowing for TP predictions based on inflow concentration and flushing. At a given inflow concentration, in-lake TP values increase by 3-fold when flushing rate increases from 0.1 to 10 per year (Fig. 1). This second-order effect of retention time on in-lake TP is asymptotic (Fig. 1). In the overall pattern, values increase sharply among lakes with modest flushing rates such that, with constant inflow concentration, in-lake TP effectively doubles when flushing rate increases from 0.1 to 1 per year (Fig. 1). Beyond this point the rate of increase declines with ever-increasing flushing rate, becoming modest at rates >2–4-times per year. This cross-system pattern suggests that, at a given input concentration, in-lake TP values are always higher in rapidly flushed lakes than those with long retention time. Depth has long been recognized as a correlate of lake fertility (Rawson 1955, Duarte and Kalff 1989) and has also contributed to the explanatory power of empirical models.

In this paper we examine how the main effects of the deterministic variables—nutrient input, hydraulic flushing rate and depth—influence reservoir nutrients across the continuum of conditions occurring in the mid-continent landscape of Missouri and southern Iowa (Fig. 2). Impetus for this analysis is the development of regional nutrient criteria for lakes and reservoirs (Gibson *et al.* 2000) and subsequent management efforts that will be applied to bring lakes into compliance. The nutrient criteria process centers on a procedural protocol that identifies regionally-unique conditions in baseline reference lakes so criteria can be established that will maintain existing water quality and protect designated uses such as water supply, recreation and fisheries. Consistent with the central premise of lake management, lakes not matching regional nutrient criteria will likely undergo load reductions to reverse eutrophication and associated impairments to aquatic life. The nutrient criteria document (Gibson *et al.* 2000) highlights that reservoirs have a broad range of hydraulic retention times and, consistent with earlier findings (Canfield and Bachmann 1981), acknowledges this unique characteristic merits consideration. Reservoirs are built for widely differing purposes, but most have large drainage areas and short detention times relative to natural lakes (Cooke *et al.* 2005). Given the effect of retention time on in-lake TP it is appropriate to evaluate the potential response of mid-continent reservoirs to nutrient load reductions and address how regional conditions might shape nutrient criteria and reservoir management in this agricultural region.

Previous limnological studies have shown the character of mid-continent reservoirs differ regionally (Jones and Bachmann 1978, Jones and Knowlton 1993, Hatch 2003). As a group, Plains reservoirs in north and western Missouri are more eutrophic than southern reservoirs in the Ozark Highlands; this gradient is tied to soil fertility, which directly influences land cover (Jones and Knowlton 1993, Jones *et al.* 2004). Forests dominate many watersheds in the Ozark Highlands whereas cropland agriculture is a major feature of the Plains. Reservoirs in Southern Iowa, located on the Central Irregular Plains ecoregion are typically more fertile than Plains reservoirs in Missouri.

Methods

Missouri limnology data come from a summer inventory of Missouri reservoirs (Fig. 2, n = 126) dating from 1978, characterized in Jones *et al.* (2004). For this analysis the data set was updated to include results from reservoir collections in 2003, 2004 and 2005; most reservoirs are represented by data from ≥ 10 summer seasons (range 4–23). Mean values of TP and total nitrogen (TN, rounded to the nearest 5 µg/L value) were calculated as nested averages over the period of record for each reservoir by calculating the geometric mean (ln-transformed) for each summer (results of 3 or 4 sampling dates) and then calculating the geometric mean
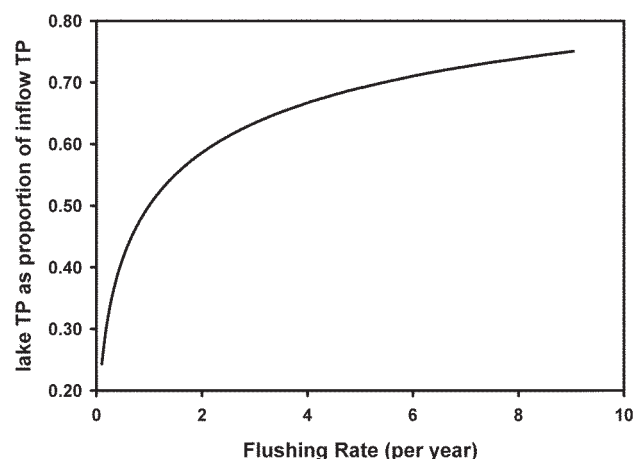

Figure 1.-Relation of in-lake TP as a proportion of inflow TP to flushing rate as estimated by the Vollenweider equation (Welch and Jacoby 2004).
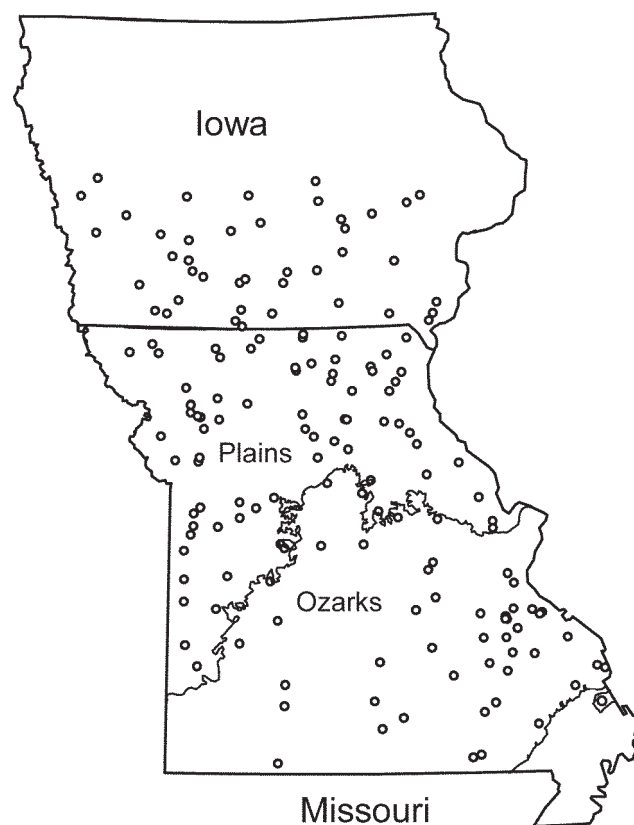

Figure 2.-Location of Missouri and Iowa reservoirs compared in this study.

Table 1.-Summary of catchment features and mean nutrient concentrations of reservoirs in this study.

	mean	S.D.	min.	median	max.
Ozarks (n=48)					
%Crop	4.9	5.2	0.0	4.6	26.2
Flushing Rate (/y)	7.8	16.5	0.2	1.5	87.1
Mean depth (m)	4.6	3.5	1.1	3.6	19.2
TP (µg/L)	25	17	6	20	67
TN (µg/L)	485	210	200	480	1060
Missouri Plains (n=78)					
%Crop	30.2	17.4	0.5	28.4	73.7
Flushing Rate (/y)	1.3	1.2	0.1	0.8	6.0
Mean depth (m)	3.5	1.5	1.5	3.2	9.6
TP (µg/L)	59	37	14	49	200
TN (µg/L)	890	290	410	900	2195
Iowa (n=41)					
%Crop	56.4	21.7	10.2	61.1	81.7
Flushing Rate (/y)	1.4	1.1	0.3	0.9	4.9
Mean depth (m)	3.4	1.0	1.5	3.9	7.2
TP (µg/L)	119	98	27	90	474
TN (µg/L)	2180	1745	900	1600	9700

across all summers. To investigate inter-annual hydrologic influences, annual April–August total precipitation in the time series was ranked for each lake. Mean nutrient data from the years with the highest and lowest rainfall total were used to characterize conditions in "wet" and "dry" years. Morphology and hydrology data (Table 1) were from the Missouri Department of Natural Resources and are described in Jones *et al.* (2004), as are Geographic Information Systems and remote-sensing techniques used to characterize cover types within the watersheds, expressed as a proportion of watershed area. In this analysis we estimated mean depth at one-forth of dam height (Jones *et al.* 2004). Hydrologic flushing rate (FR/year) was estimated for each reservoir using regional runoff coefficients (MDNR 1986), watershed area, and reservoir volume. According to limnological theory, flushing rate exerts an asymptotic influence on lake nutrient concentrations, so we evaluated effects using a Flushing Index (FI) based on a version of the Vollenweider equation (Welch and Jacoby 2004):

$$\text{Flushing Index} = (1 + FR^{-0.5})^{-1}$$

Based on results presented in Jones *et al.* (2004), reservoirs with >50% urban cover are unique within the data set and were excluded from this analysis. We separate Missouri reservoirs regionally into the Ozark Highlands, part of the Eastern Broadleaf Forest Ecological Province (Nigh and Schroeder 2002), and the Plains, part of the Temperate Prairie Parkland Ecological Province (Table 1; Fig. 1). This approach simplifies an earlier categorization (Jones and Knowlton 1993) that divided the Plains into glaciated and

unglaciated and included an ecotonal region (Ozark Border) between the Plains and Ozarks (Thom and Wilson 1980). Iowa nutrient data were taken from Hatch (2003) and include measurements from only one summer per reservoir (1990 or 1992). Iowa morphology, hydrology and land cover data were from Bachmann *et al.* (1980). In this exploratory analysis, data were limited to reservoirs located in southern Iowa (below 42° N latitude) to most closely match the lake type, landscape and land cover immediately to the north of Missouri. We excluded data from reservoirs with large upstream impoundments (n = 9) and those with inputs dominated by groundwater (n = 2).

Relations between landscape variables and nutrients were examined by least-squares methods of single and stepwise multiple regression and analysis of covariance with $p < 0.05$, unless otherwise stated. Data were transformed using natural logs (ln) or logit (adding 0.003 to cover types to avoid zero values) where appropriate. All analyses were performed with SPSS for Windows (version 13) or SAS (version 9.1).

Results

Regional reservoir and watershed characteristics

Regionally, nutrient levels were least among reservoirs in the Ozark Highlands (n = 48) where median TP was 20 µg/L and ranged from 6 to 67 µg/L; median TN was 480 µg/L and ranged from 200 to 1060 µg/L (Table 1). Most watersheds in the Ozarks have <5% cropland, and only one supports

Table 2.-Simple and multiple regressions for cross-regional data (n = 167 reservoirs) and region-specific multiple regressions of effects on TP and TN (ln-transformed) of % cropland (logit-transformed), mean depth (Z – ln-transformed) and Flushing Index (FI – ln-transformed). Non-significant coefficients (p > 0.05) are not shown. For TP, ANCOVA showed coefficients for depth (Z) and flushing index (FI) did not significantly differ (p > 0.05) among regions. For TN, inter-regional differences were significant for all three variables.

#	group	Regression Model	r^2	RMSE
1	all	$TP_{ln} = 4.312 + 0.363 \times \%crop$	0.60	0.54
2	all	$TP_{ln} = 5.032 + 0.374 \times \%crop + 1.037 \times FI_{ln}$	0.69	0.48
3	all	$TP_{ln} = 5.299 + 0.357 \times \%crop + 0.740 \times FI_{ln} - 0.405 \times Z_{ln}$	0.73	0.45
4	Ozarks	$TP_{ln} = 5.233 + 0.392 \times \%crop + 0.592 \times FI_{ln} - 0.400 \times Z_{ln}$	0.77	0.34
5	Plains	$TP_{ln} = 5.309 + 0.160 \times \%crop + 1.191 \times FI_{ln} - 0.306 \times Z_{ln}$	0.60	0.38
6	Iowa	$TP_{ln} = 5.927 + 2.017 \times FI_{ln}$	0.29	0.54
7	all	$TN_{ln} = 7.173 + 0.305 \times \%crop$	0.69	0.37
8	all	$TN_{ln} = 7.431 + 0.309 \times \%crop + 0.372 \times FI_{ln}$	0.71	0.36
9	all	$TN_{ln} = 7.549 + 0.301 \times \%crop + 0.241 \times FI_{ln} - 0.179 \times Z_{ln}$	0.73	0.35
10	Ozarks	$TN_{ln} = 7.414 + 0.264 \times \%crop - 0.297 \times Z_{ln}$	0.74	0.23
11	Plains	$TN_{ln} = 7.271 + 0.148 \times \%crop + 0.511 \times FI_{ln}$	0.55	0.22
12	Iowa	$TN_{ln} = 8.300 + 0.283 \times \%crop + 1.299 \times FI_{ln}$	0.43	0.43

>17%; Flushing Rate was 0.23–87/year, and mean depth was 1.1–19.2 m (Table 1). Nutrient levels in the 78 Missouri Plains reservoirs are roughly double those measured in the Ozarks (Table 1); among these, median TP was 49 µg/L and ranged from 14 to 200 µg/L, while median TN was 900 µg/L and ranged from 410 to 2195 µg/L (Table 1). Cropland was <1–74% of total watershed area (median = 30%crop); Flushing Rate was 0.1–6/year, and mean depth was 1.5–9.6 m (Table 1). Reservoirs in southern Iowa have about twice the nutrient levels of the Missouri Plains (n = 41, median TP = 90 µg/L and median TN = 1600 µg/L). Over half the Iowa watersheds had >50% crop cover, and only 5 of 41 catchments had <30% cropland. Flushing Rate in Iowa was 0.3–4.9/year (Table 1).

Cross-regional patterns

Among these 3 regions there was a strong cross-system relation ($r^2 \geq 0.6$, n = 167) between reservoir nutrients and the proportions of cropland cover (%crop) in their respective catchments (Fig. 3; Table 2). A cropland-nutrient relation was detailed by Jones *et al.* (2004) for Missouri reservoirs, but the Iowa data fit nicely within the pattern and double the original range of the nutrient continuum. This cross-regional pattern shows a general increase in reservoir nutrient concentration from south-to-north such that latitude is a strong correlate of both TP_{ln} (r = 0.60) and TN_{ln} (r = 0.73), reflecting the measurable increase in cropland agriculture along this geographic axis (r = 0.72 between cropland and latitude).

In contrast, there was no strong cross-regional pattern between nutrients and Flushing Index (Fig. 4; $r^2 \leq 0.03$, n = 167). Within regions, however, the relation between nutrients and Flushing Index was strong within the Missouri Plains (r
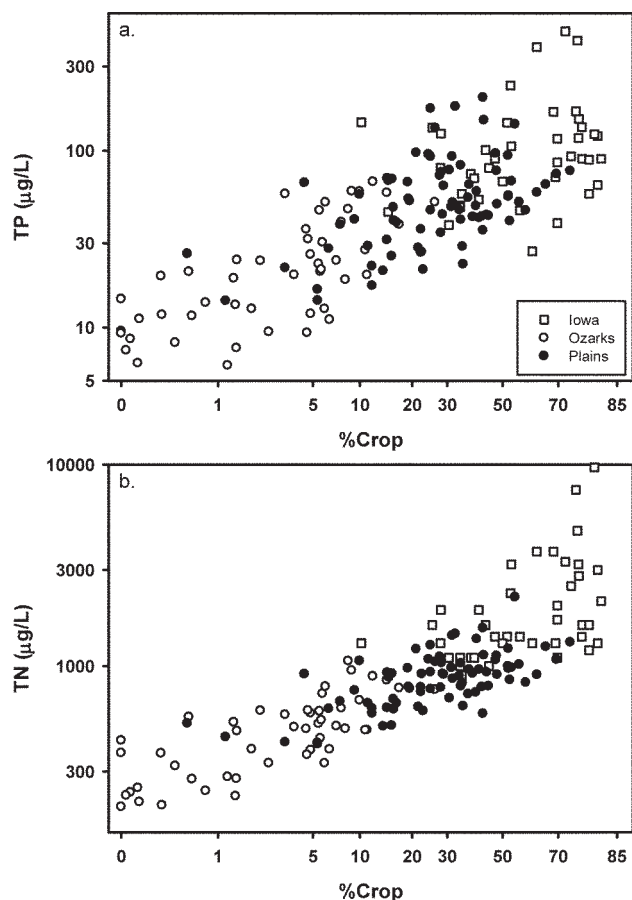

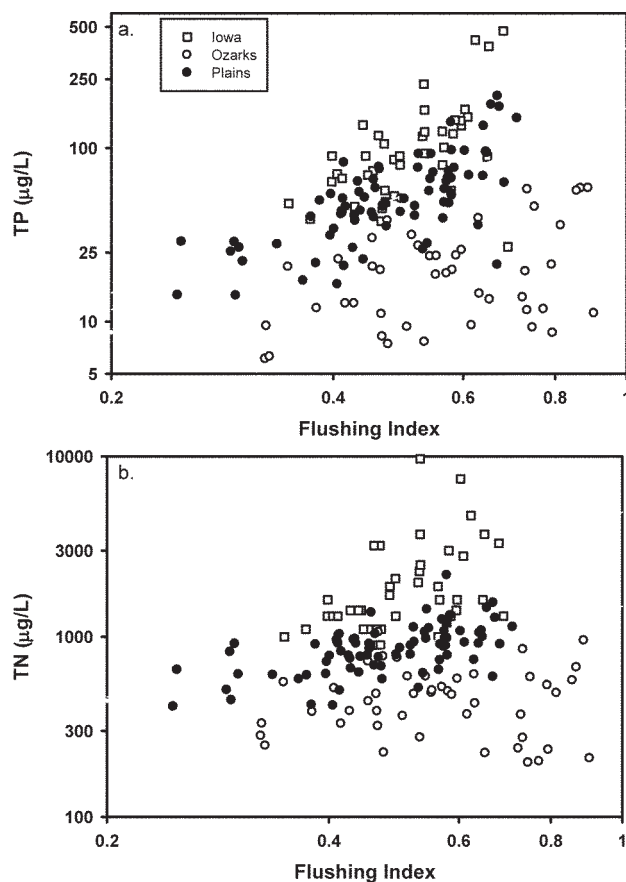**Figure 3.-**Relation of TP and TN (ln-transformed) to %crop (logit-transformed).

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Figure 4.-Relation of TP and TN to Flushing Index (ln-transformed).

= 0.57 for TP and 0.70 for TN, n =78), weaker among Iowa reservoirs (r = 0.54 for TP and 0.45 for TN, n = 41), and among Ozark reservoirs the correlation was nonsignificant for TN and weak for TP (r = 0.33, p = 0.02). Omitting the most rapidly flushed Ozark reservoirs (>5/year) did not change this result. For both nutrients, multiple regressions showed Flushing Index accounts for residual variation not attributable to cropland (Table 2). Within the cross-regional data set, nutrients were also negatively related to depth (r = −0.405 for TP and −0.27 for TN, n = 167) which accounts for additional residual variation in TP and TN in multiple regression models (Table 2).

Region-specific patterns

Deterministic variables accounting for cross-system patterns in reservoir nutrients differed in importance among regions. Based on partial r^2 values from multiple regressions (Table 2), %crop accounted for the greatest amount of explained variation for TP in the Ozarks (51%), and TN in all three regions (Ozarks 58%, Plains 41%, Iowa 27%). For TP in the Missouri Plains and Iowa, however, Flushing Index was

the dominant variable accounting for 49% and 29%, respectively, of TP variability. Across the range of TP values in Iowa reservoirs, effects of %crop and mean depth were not statistically significant. In the Missouri Plains, %crop and mean depth accounted for only 7% and 4%, respectively, of TP variability. These interregional differences in explanatory power of the deterministic variables occurred even though regression slopes for Flushing Index and mean depth were not statistically different among regions for TP (ANCOVA, p > 0.05). For TN, slopes for all 3 variables differed among regions. Mean depth accounted for 16% of TN variability among Ozark reservoirs but was not significant elsewhere. Flushing Index was not significant in the Ozarks, but accounted for 13% of TN variation in the Missouri Plains and 15% in Iowa.

Differences in nutrient-%crop relations in our data suggest interregional differences in soil fertility, climate and agronomic practices influence the overall pattern. Based on the analyses, TP and TN concentrations are more sensitive to changes in %crop in the Ozarks than the Missouri Plains. Reasons for these differences are beyond the scope of this assessment but likely reflect effects of thin, permeable Ozark soils and associated higher runoff. Soils have less capacity to retain nutrients when contact with infiltrating precipitation is brief. Iowa data suggest %crop has less influence on TP and a greater influence on TN than in Missouri. In fact, due to inter-lake variation, the effect of %crop on TP in Iowa is not significant (Table 2) unless Iowa and Missouri data are combined to show the overall continuum (Fig. 3). For TN, concentrations in Iowa were much greater than Missouri reservoirs with similar catchments and morphology (Fig. 3), a difference reflected in the large intercept in the Iowa TN model (Table 2). An Iowa reservoir with median %crop and Flushing Index for this data set (25% crop, FI = 0.52) is predicted to have 1255 µg/L TN compared to 874 µg/L in the Missouri Plains. These differences likely reflect regional agronomic practices, other deterministic factors not considered, and inherent variability in limnological data. Reservoir nutrients vary widely from year to year (Knowlton *et al.* 1984, Knowlton and Jones 2006a, 2006b), and the Iowa data set is based on a single sampling season compared to an average of 10 years for Missouri. For this reason, we have more confidence that Missouri results reflect genuine inter-regional differences with predictive value. In the following sections quantitative analysis is restricted to Missouri reservoirs. Iowa data, however, clearly demonstrate the overall continuum of land use effects (Fig. 3) and corroborate the strong influence of hydrology among prairie reservoirs.

"Wet" versus "dry" years

Regression results (Table 2) indicate hydrology has a greater role in controlling nutrients in the Missouri Plains than among Ozark reservoirs. Inter-annual comparisons between

the "wettest" (highest April–August rainfall) and "driest" (lowest rainfall) years in the multi-year Missouri data set (Iowa reservoirs were sampled in only one year and were not included) provide an independent test of this inter-regional difference. The expectation that flushing rates are larger in wet years, resulting in higher nutrients, was partly supported by the analysis. The results demonstrate the role of hydrology is stronger than other factors influencing temporal variation in individual reservoirs and the cross-system pattern. In the Missouri Plains some 91% of reservoirs had higher TP in the wet year, averaging 43% larger than the dry year. In the Ozarks, only 60% of reservoirs had higher TP in the wet year, with a mean difference of 16%. This result is consistent with differences in the slopes and partial r^2 for Flushing Index between the Plains and Ozarks (Table 2). For TN, however, wet versus dry year comparisons showed an average difference of only 5% in the Missouri Plains compared to 21% in the Ozarks. This result contrasts with the stronger effects of Flushing Index in the Plains regression analysis.

Implications for nutrient reduction, nutrient criteria and management

Our predictive equations (Table 2) indicate large-scale nutrient reduction in Midwestern reservoirs will require massive changes in land use to reduce inflow concentrations. In the Missouri Plains, for example, reducing %crop from 60% to 30% (from near maximum to near median; Table 1) – reduces TP and TN by only about 20% when other factors are held constant. For Ozark reservoirs decreasing %crop from 10 to 5% (from near maximum to near median; Table 1) reduces TP by 25% and TN by 17%. These results suggest that lake trophic state improvements in the form of cropland conversions to grass or forest, or implementation of nonpoint management programs, will not be proportional to efforts required to obtain them.

Another consideration is that the models show hydrology places added limits on reducing reservoir nutrients. Consistent with theory (Fig. 1), at any given %crop level (inflow concentration), regression models for Missouri Plains reservoirs predict TP values effectively double between Flushing Index values of 0.25 and 2 (Fig. 5). Values are even broader across the full range of flushing rates within the region (Table 1). By comparison, at a fixed flushing rate value, TP would effectively double in a Plains reservoir if %crop increased from ~5% to ~70%, which is effectively the entire range of cropland within the Missouri Plains data set.

Given the influential role of Flushing Index, reservoirs with sharply differing land cover can support identical TP values. For example, the median TP value of 49 μg/L in the Missouri Plains (Table 1) would be expected in reservoirs with 50%crop and FR = 0.5, 30%crop and FR = 0.75, 20%crop and FR = 1, or 6%crop and FR = 2. Values of TP > 49 μg/L
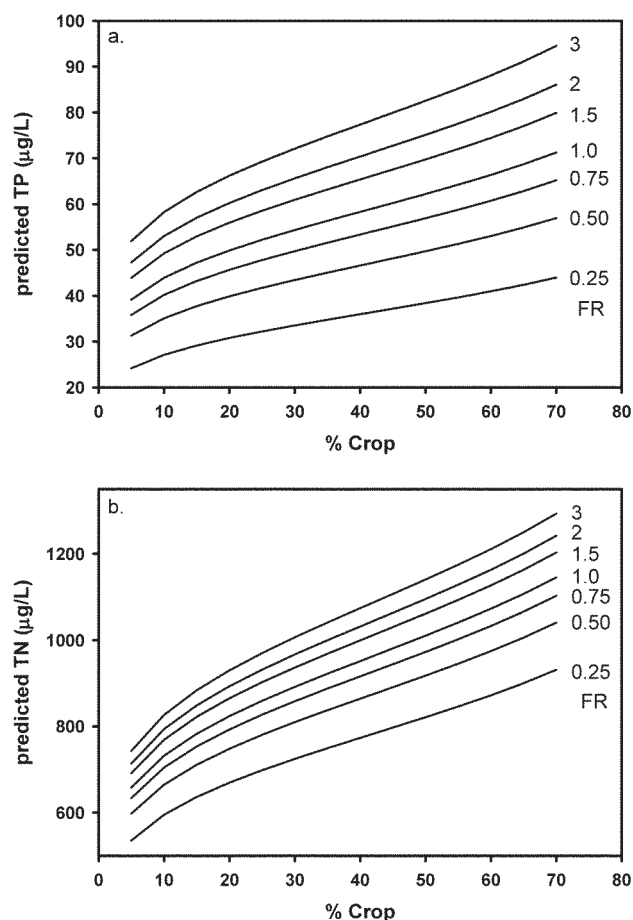

Figure 5.-Response of TP and TN to variation in %crop and flushing rate (FR) for reservoirs in the Missouri Plains as predicted by equations 5 and 11 in Table 2.

are the general rule among reservoirs with >20%crop and FR > 1, but even Plains reservoirs with modest cropland would support such TP levels if hydraulic residence time is short (Fig. 5). These illustrations show Plains reservoirs with large catchments and minimal cropland have TP values that match levels found in impoundments located in agricultural watersheds with modest flushing rates. This comparison highlights the importance of impoundment location within the landscape as a factor determining reservoir trophic state.

The nutrient content of reservoirs of similar size and depth constructed in catchments with identical land cover will be determined by hydraulic residence time (Fig. 5). All other factors equal, the reservoir with the larger watershed will have larger flushing rate and higher nutrients than reservoirs positioned in small catchments. Consequently, rapidly flushed reservoirs are unlikely to be brought into compliance with the

same nutrient standards as slowly flushed reservoirs without far greater management intervention.

The nutrient criteria effort centers on conditions in regional baseline reference lakes to establish criteria to maintain existing water quality and protect designated uses (Gibson *et al.* 2000). Data ranking can also be used to identify criteria and the trisection method (median of the lowest third of the ranked long-term reservoir mean values in our data set) resulted in mock reference values for the Missouri Plains reservoirs of 27 µg/L TP and 620 µg/L TN. Plains reservoirs with long-term means that fit within these mock reference criteria, however, averaged less than half the %crop, double the %forest, and hydraulic residence times 3 times longer than noncompliant reservoirs. Based on the regional regression equation (equation 5, Table 2), a Missouri Plains reservoir with median crop cover (28%), depth (3.2 m) and FR (0.8/year; Table 1) would support 61 µg/L TP, or about twice the mock target value, and would match the TP criterion only if %crop were limited to <1% of its catchment (Fig 5a). Even located in a watershed without cropland, the shallowest and most rapidly flushed Plains reservoirs support ~40 µg/L TP. Thus, for some reservoirs, complete elimination of cropland would be insufficient to meet criteria based on water bodies with lower input concentrations and longer hydraulic residence time. For reservoirs with median flushing rate, %crop would need to be <5% to meet the TN criterion (Fig 5b).

Discussion

This analysis shows distinguishable regional differences in the relative importance of the 3 key explanatory variables—nonpoint source nutrient loading (cropland), hydrology and morphology—on reservoir nutrients (Table 2). All 3 variables are known to directly influence in-lake nutrient concentrations and have been the central metrics of empirical, cross-system lake models for several decades (Edmondson 1961, Vollenweider 1975, Cooke *et al.* 2005). The relations are based on the widespread understanding that nutrient loading and residence time largely determine lake and reservoir water quality (Jones and Bachmann 1976, Jørgensen 2003, Windolf *et al.* 1996). Most analyses have concentrated on phosphorus, but these same explanatory variables have been shown to determine in-lake nitrogen levels (Bachmann 1980, Bachmann 1984, Jensen *et al.* 1990, Windolf *et al.* 1996).

Among these Midwestern reservoirs the strong south-to-north increase in nutrient levels (Table 1, Fig. 3), which amount to a nearly 4-fold increase in median TP and 3-fold increase in median TN, is opposite the latitude-dependent global pattern (Kalff 1991). The reservoir nutrient pattern directly parallels the increase in ambient soil fertility along this axis and the general northward increase in the intensity of agricultural practices such as crop production and associated nutrient application (Jones and Knowlton 1993, Arbuckle

and Downing 2001). Strong correlations between stream nutrient concentrations in Missouri and the proportion of cropland in their catchments (Perkins *et al.* 1998) provide the basis for using %crop as a surrogate for inflow nutrient concentrations (Jones *et al.* 2004). Additional support for this approach comes from the sharp increase in stream nitrate levels in Iowa with cropland (Schilling and Libra 2000). The regional stream nutrient-cropland relation (Perkins *et al.* 1998) suggests baseflow concentrations of phosphorus and nitrogen double or triple across the range of crop cover found within the Missouri Plains and Iowa (Table 1). Nutrient concentration of inflowing water is considered the best single indicator of in-lake concentrations (Ahlgren *et al.* 1988), and high external loading from agricultural landscapes largely accounts for the mostly eutrophic and hypereutrophic condition of these Midwest reservoirs (Table 1; Fig. 3). Few reservoirs in the region have point source inputs.

These results are preliminary, and better estimates of reservoir nutrient loading and flushing rate would aid in modeling reservoir response to management and account for inconsistencies in the analysis. For example, given the stronger effect of flushing on TP and TN in the Missouri Plains than the Ozarks, we expected Plains reservoirs to show larger differences between "wet" and "dry" years. This was the case for TP but not for TN. Also our quantification of the effect of hydrology on reservoir nutrients is imprecise given that region-specific slopes for the effect of Flushing Index on TP (Table 2) range from 0.59 (Ozarks) to 2.02 (Iowa) but are not statistically significant. Regardless, these findings represent the best estimate of these deterministic variables exert controlling influence on reservoir nutrients. The analysis highlights the powerful influence of hydrology in both Missouri and Iowa. Implementation of nutrient criteria without specific consideration of hydrology runs the risk of creating unrealistic and unrealizable standards.

A key aspect of incorporating hydrology into nutrient criteria assessment is to explicitly recognize the additional potential of managing nutrients by manipulating lake morphology and hydrology. Reservoir depth, volume, and watershed size are determined by design specifications and location of the constructions site within the valley. Collectively, these features determine hydraulic retention time. For existing reservoirs, increasing the dam height to increase retention time may be a cost-effective means of improving water quality. In a well-documented example, McDaniel Lake in the Missouri Ozarks exhibited a ~40% decline in summer (July–September) mean TP after the spillway crest was raised 1.2 m (Youngsteadt 2005). During the 20-year study, multiple lake and catchment improvement measures were ongoing, but retrospective analysis ascribed 61% of the TP decline to direct effects of raising the water level and another 10% to cooler hypolimnetic temperatures resulting from the deeper basin. In contrast, substantial efforts to reduce

tributary TP accounted for only 20% of the improvement. Reservoirs built with inadequate depth and residence time, or those that have lost volume through in-filling, could benefit substantially from similar modification. Compliance with nutrient criteria should recognize this potential means of water quality control.

This analysis highlights that basin depth, catchment size and resulting hydrologic features of constructed reservoirs are design decisions that have direct effects on water quality. Likewise, most reservoirs were built long after presettlement vegetation was altered for agriculture, so nutrient loads were in place prior to creating artificial lakes on the landscape. These are fundamental differences between natural and artificial lakes and should be considered when setting nutrient criteria.

Conclusions

The major conclusion of this assessment is that dramatic nutrient reduction in Midwestern reservoirs is unlikely, particularly in the most highly flushed reservoirs. The influential role of hydraulic flushing adds additional management challenges for compliance with regional nutrient criteria. Our illustration using the trisection method to set mock nutrient criteria shows target values can be unattainable in highly flushed reservoirs. Further, the analyses suggest that hydraulic flushing rate must be considered when setting nutrient criteria. It is unreasonable to set nutrient criteria based on water bodies with long hydraulic retention time and apply them to rapidly flushed lakes. This consideration must be a factor when identifying regionally unique conditions in baseline reference lakes or by ranking regional lakes after separating them along a continuum of flushing rate values.

Another important consideration for implementation of nutrient criteria is the quantitative significance of temporal variation in measuring reservoir characteristics. As illustrated by differences between wet and dry years for TP in the Plains and TN in the Ozarks, reservoirs are not constant over time. Variation among individual (unaveraged) TP measurements can exceed 10-fold within a single reservoir (Jones and Knowlton 2005). For the typical Missouri reservoir, 5 summers of averaged data (3–6 samples per summer) are required to estimate mean TP with 95% confidence limits spanning less than a factor of 2 (Knowlton and Jones 2006b). Determining the current nutrient status of a reservoir with sufficient precision to evaluate its compliance with a given nutrient standard thus requires relatively long-term monitoring. Also, improvements resulting from efforts to comply with nutrient standards are likely to be obscured by ordinary background variation.

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