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Inland Waters

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tinw20

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To cite this article: John R. Jones , Carol Pollard & Daniel V. Obrecht (2020): Factors influencing phosphorus in midcontinent impoundments (USA) and challenges for detecting abatement, Inland Waters

To link to this article: https://doi.org/10.1080/20442041.2020.1816802

Published online: 21 Dec 2020.

INLAND WATERS
https://doi.org/10.1080/20442041.2020.1816802

RESEARCH BRIEF

Factors influencing phosphorus in midcontinent impoundments (USA) and challenges for detecting abatement

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ABSTRACT
Impoundments in the midcontinent region of the United States provide the beneficial services of lentic waters. These impoundments were constructed long after intensified agriculture was established, and most are eutrophic. Total phosphorus (TP) increases in regional streams and reservoirs, concurrent with the proportion of cropland in the watershed, serve as a surrogate for nutrient loading from agriculture. The potential impact of external loading of TP to these reservoirs is moderated by sedimentation of particulate P and plunging interflows during summer stratification. Hydrology has a strong influence on TP; cross-system analyses show TP more than doubles across the range of flushing rates found in Missouri reservoirs when other factors are held constant. This link between hydrology and TP suggests reservoir placement on the landscape and design criteria strongly influence trophic state. Temporal variation is such that summer mean TP typically ranges 2- or 3-fold in individual reservoirs, suggesting benefits of best management practices to reduce external loading may be masked by inherent variation. Eutrophication of a midcontinent reservoir from poultry litter has been documented. Expansion of industrialized animal production throughout the region suggests legacy P, and resulting eutrophication, will likely increase over time without regulation.

ARTICLE HISTORY
Received 21 February 2020
Accepted 21 August 2020

KEYWORDS
BMPs; impoundments; phosphorus loading; temporal variation

Introduction

Drawing from case studies, Hasler (1947) presented limnologists with a clarion statement linking eutrophication to inadvertent fertilization from domestic sources. Subsequently, reversal of conditions in Lake Washington provided a successful illustration of the benefits of wastewater diversion and a template for lake restoration (Edmondson 1961). Vollenweider (1975) used phosphorus loading, lake morphology, sedimentation, and hydrology in steady state equations to compute lake phosphorus. These models serve as a conceptual basis for quantifying among-lake variation and predicting responses to changes in external loading (Brett and Benjamin 2008).

This analysis addresses conditions determining phosphorus levels and the potential for detecting nutrient abatement in constructed impoundments in the midcontinent region of the United States (Iowa and Missouri; Fig. 1). Located below the latitude where glacial lakes prevail, these reservoirs provide the various beneficial services of lentic waters. They are positioned in valleys, formed by stream erosion, typically with 1 or 2 major inflows from watersheds large enough to maintain stable water levels. Most have been constructed in the past 60 years in landscapes dominated by a continuum of agriculture and forests.

Cross-system variation of total phosphorus (TP) in these reservoirs is strongly related to the proportion of cropland in the watershed (mostly maize and soybeans), which serves as a surrogate for nonpoint nutrient loading from agriculture (Jones et al. 2004, 2008a, 2009). Influences of reservoir depth (negative coefficient) and hydrologic flushing rate (FR, positive coefficient, determined by volume and watershed size) further explain observed variation. These metrics are consistent with components included in Vollenweider's model and illustrate that these reservoirs broadly conform to the external loading paradigm. Regionally, a 4-fold increase in mean reservoir TP occurs from south to north that follows an increase in ambient soil fertility and a gradient from forests to intensive agriculture (Arbuckle and Downing 2001, Jones et al. 2008a). Most reservoirs located in large watersheds dominated by cropland are eutrophic or hypereutrophic (Jones et al. 2008a, 2008b) with TP levels 3-times greater than deep basins in forested catchments. In this respect, reservoirs reflect their edaphic location.

Most cropland in Missouri was prairie at the time of Euro-American settlement (Jones et al. 2009). Plowing

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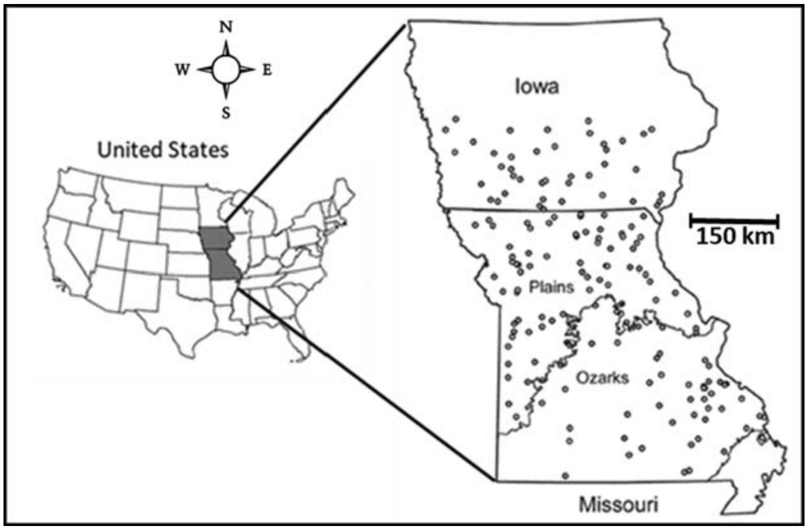

Figure 1. Location of impoundments in Iowa and Missouri (USA), redrawn after Jones et al. (2008a).

prairies and clearing forests for agriculture greatly increased nutrient loss from these landscapes (Smith et al. 2003). Anthropogenic impoundments were constructed long after nutrient loading from agriculture was in place, and analyses suggest most have been fertile from the time of dam closure (Jones et al. 2009). Date of reservoir construction was not significant in cross-system models, implying current age does not stand out as a source of variation (Carney 2009, Jones et al. 2009). Few receive domestic wastewater, but responses to these inputs have been detailed in several cases (Knowlton and Jones 1989, 1990, Obrecht et al. 2005).

Herein, we describe reservoir processes to show the challenges of assessing best management practices (BMPs) for improving water quality in midcontinent reservoirs (Fig. 1). Evidence suggests nutrient reduction from nonpoint source mitigation will most likely be small (Osgood 2017) and within inherent temporal variability found in impoundments (Knowlton et al. 1984, Knowlton and Jones 1995, 2006a). Overall, such measures will likely be imperceptible, insufficient, or both. We also address the potential for increased eutrophication from the expanding confined animal husbandry industry in the region and highlight that inputs from this source are preventable.

This evaluation draws on long-term study of midcontinent reservoirs (Jones and Bachmann 1978a, Jones and Bachmann 1978b, Jones et al. 2020) and serves as a summary of current understanding of controlling factors. The analysis centers on TP as the causal variable in reservoir eutrophication. The link between TP and algal chlorophyll in these systems has been evaluated extensively (Jones and Bachmann 1976, Hoyer and Jones 1983, Jones and Knowlton 2005a, Jones et al. 2008b, Yuan and Jones 2020).

Background of reservoir processes in the midcontinent (USA)

Comparison of reservoirs and natural lakes

A comparison between reservoirs and natural lakes in Iowa's agricultural landscape showed that, at a given loading value, open water TP values were considerably lower in reservoirs than nearby natural lakes (Jones and Bachmann 1978a, 1978b). Estimating TP in Iowa reservoirs required increasing the P sedimentation coefficient by 2 orders of magnitude relative to natural lakes (Jones and Bachmann 1978b). A nationwide analysis predicted TP equally well in both lake types by using distinct P sedimentation coefficients for each (Canfield and Bachmann 1981). In that dataset, areal P loading, hydraulic flushing, and P sedimentation all averaged some 5–7 times greater among reservoirs, which further highlights fundamental differences relative to natural lakes.

Two factors contribute to the disparity in external TP loading between these lake types. First, Jones and Bachmann (1978b) hypothesized that TP inputs to reservoirs were partly associated with inorganic suspended materials delivered by streams from erosional topography, which would subsequently sediment from the water column. Supporting this view was that summer TP in natural lakes averaged 97% of spring levels while reservoirs retained only 37%. This seasonal pattern is also apparent in daily sampling of Lake Woodrail, Missouri (Fig. 2). Maximum TP levels were associated with spring inflows and decreased by >70% within weeks. These data show reservoir TP can change rapidly. Nephelometric turbidity (Fig. 2b–c) showed declines of ~70% within a week following the spring maximum, suggesting terrigenous materials and associated P sediment

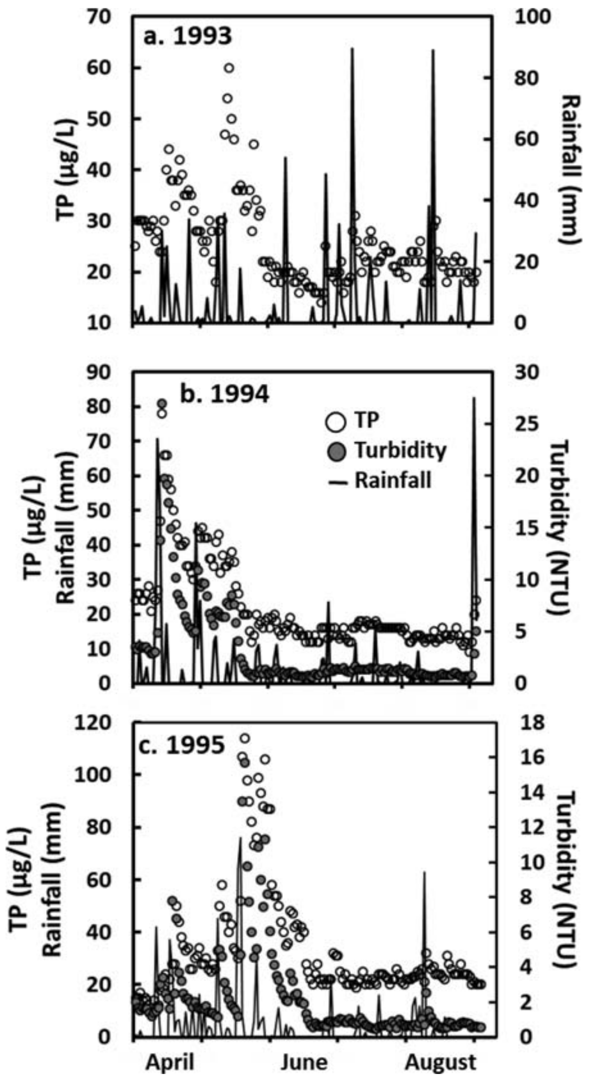

Figure 2. Daily total phosphorus (TP) sampling of Lake Woodrail, located in Columbia, Missouri, are included with daily rainfall during spring to summer (a) 1993, (b) 1994, and (c) 1995. Nephelometric turbidity data are included for 1994 and 1995.

following spring–early summer inflow; others report sedimentary loss of TP is directly linked to particle size and water residence time (Canfield et al. 1982, Knowlton and Jones 1995, Effler et al. 2002). The general cross-system decline of nonvolatile suspended solids (NVSS: mg/L) in Missouri reservoirs during summer provides additional support (Jones and Knowlton 2005b).

Second, inflow potentially affects the entire waterbody when the water column is mixing or weakly stratified, whereas during summer stratification inflows plunge as an underflow into deep strata, as determined by density (Knowlton and Jones 1995, Effler et al. 2009). Nutrient and sediment loading to the surface strata therefore depend on timing of inflow relative to thermal stratification. Plunging inflows effectively blunt the

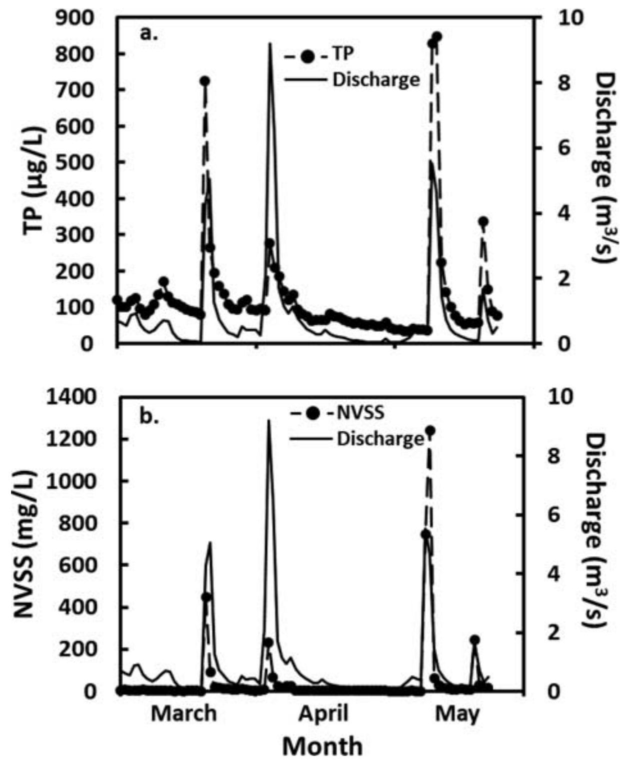

Figure 3. Short-interval sampling of total phosphorus (TP) and non-volatile suspended solids (NVSS) collected from Hinkson Creek located in Columbia, Missouri. Redrawn from Perkins and Jones (1994).

influence of external loading on the trophogenic zone. This flow pattern differed among years in Lake Woodrail (Fig. 2). During peak summer stratification, when surface temperatures averaged 27 °C (and commonly were >30 °C), surface TP showed only modest response to rain events, suggesting plunging inflow. Plunging inflow was clearly demonstrated in 1993 when summer rainfall totaled >530 mm, with several storms delivering 50 to >80 mm (Fig. 2a), resulting in only modest change in surface TP. Turbidity data also showed little response to rain events during summer stratification (Fig. 2b–c).

Short-interval sampling of Hinkson Creek, which includes Lake Woodrail in its watershed (Perkins and Jones 1994), illustrates the sharp increase in both TP and NVSS on the ascending limb of spates followed by rapid declines (Fig. 3). The correlation between these parameters was $r = 0.84$ ($n = 83$, log transformed). Some 80% of TP was particulate in this dataset, with ~9% of the total as soluble reactive P (flow weighted), indicating bioavailable P is a modest fraction of the total. Stream temperature decreased by 1–3 °C during these events, which would promote plunging inflow in impounded water during summer stratification. The inference is that streams delivering flow to midcontinent impoundments would share, to some degree, the pattern measured in Hinkson Creek.

Factors that determine total phosphorus in midcontinent reservoirs

Some two-thirds of cross-system variation in mean TP in Missouri reservoirs is explained by nonpoint input associated with current land use, as modified by basin morphometry and hydrology (Jones et al. 2004, 2008a, 2009). TP relates positively with cropland and negatively with forest (Fig. 4; Jones et al. 2008a) while grassland was an intermediate source (not shown). Even among reservoirs with >80% forest and grass in the watershed, cropland accounted for most cross-system variation. Data from Iowa reservoirs fit this pattern and double the TP range measured in Missouri (Fig. 4; Jones et al. 2008a).

A statewide inventory of Missouri streams shows a distinct increase in baseflow TP with cropland and decrease with forest cover, which supports assumptions about TP loading from the landscape (Fig. 5). Baseflow TP increases some 40-fold (from <5 to >200 µg/L) across the range of cropland in these watersheds (<1% to >80%, Fig. 5), with mean TP increasing by an order of magnitude between crop cover of near zero to 4% (Fig. 5). This pattern reflects differences in ambient soil fertility, fertilization, and related agricultural activity across this continuum. The landscape pattern

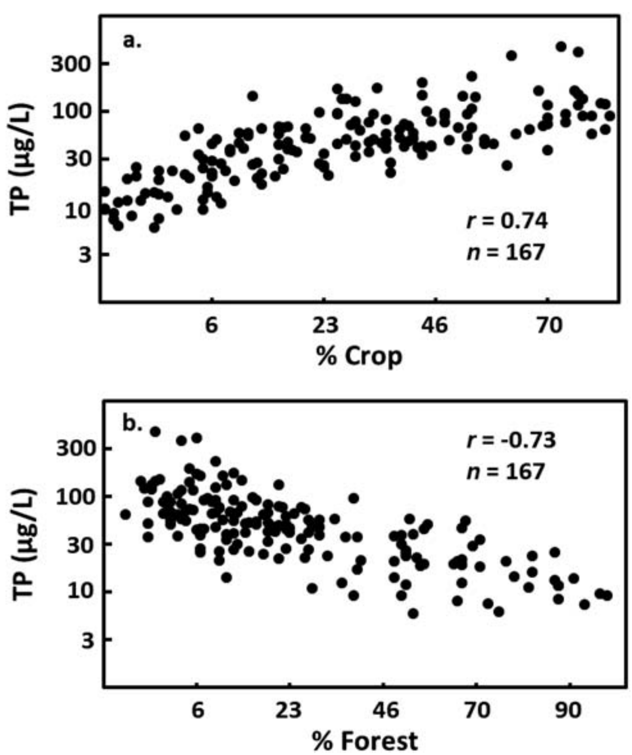

Figure 4. Total phosphorus (TP, log transformed) in Missouri and southern Iowa reservoirs plotted against % cropland and % forest cover in the watershed (both logit transformed). Data from Jones et al. (2008a).

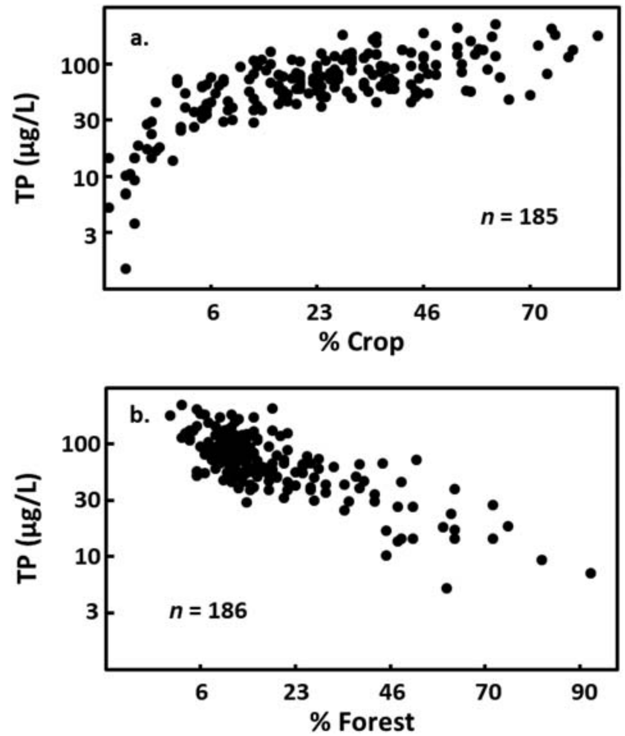

Figure 5. Baseflow data total phosphorus data (TP, log transformed) from streams located statewide in Missouri plotted against % cropland and % forest cover in the watershed (both arcsine square root transformed).

between stream TP and cropland further supports that external loading accounts for predominately eutrophic reservoirs in agricultural catchments (Jones et al. 2008a, 2008b). Data from instrumented watersheds in northern Missouri reinforce this conclusion; loss of TP was ~9 times greater from row crop than forested watersheds (3.82 vs. 0.43 kg/ha/yr; Udawatta et al. 2011). Lake models show inflow concentration has a primary role in determining in-lake concentrations, other factors being equal (Brett and Benjamin 2008).

Hydrology strongly influences TP in these impoundments; increasing the flushing rate (FR) can double reservoir TP at any given proportion of cropland in the catchment while holding depth constant (Jones et al. 2008a). By contrast, holding FR and depth constant, TP would effectively double when cropland was increased from 5 to 70%, which represents nearly the full range in the region. Given these influences, the median TP value of 49 µg/L in reservoirs located in Missouri's historic prairie region could be found 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 (Jones et al. 2008a). This analysis suggests reservoirs with large watersheds and rapid flushing will support eutrophic TP values even when the majority of the watershed is not cropland. Noteworthy is the importance of landscape placement (watershed size and land cover) and design (depth) on reservoir trophic state.

Mesotrophic conditions occur in several impoundments in the prairie region of Missouri; these have low FR and catchments with forest cover (Jones et al. 2009). In Iowa reservoirs, both TP and cropland averaged about twice that of agricultural reservoirs in Missouri (59 vs. 119 µg/L and 30% vs. 56% respectively; Jones et al. 2008a). Among Iowa reservoirs, cropland was not significant in cross-system analyses but FR was, which corroborates the strong influence of hydrology in prairie reservoirs (Jones et al. 2008a). The importance of hydrology on reservoir limnology was previously documented by Straskraba (1999).

Temporal variation in midcontinent reservoirs

Temporal variation in these reservoirs is wide-ranging, both among individual summer samples from a given reservoir and seasonal means over time. In 6 summers of daily collections from Lake Woodrail, 15% of individual TP samples were ≥150% of the mean and 6% were more than double the mean. Results were similar in statewide reservoir monitoring based on summer sampling (Knowlton and Jones 2006a). In Lake Woodrail, mean summer TP varied by >2-fold during 6 seasons, and mean values from statewide monitoring commonly varied among years by 2- or 3-fold. Variation in TP among individual samples can exceed 10-fold in a given reservoir over time (Jones and Knowlton 2005a). Consequently, nutrient reduction measures would need to be large to stand out against temporal variation inherent in these impoundments.

Data from Lincoln Lake illustrate temporal variation in both TP and NVSS. During 1989–2016, TP averaged 23 µg/L with summer means of 13–47 µg/L, which is a >3-fold difference ($n = 27$; Fig. 6a). Some 18% of mean TP values were ≥150% the overall average. NVSS averaged 3.6 mg/L with seasonal means of 1.7–9.9 mg/L, a nearly 6-fold difference (Fig. 6b). Like TP, ∼18% of mean NVSS values were ≥150% the overall average. These metrics were strongly correlated ($r = 0.89$, $n = 27$), which reflects particulate P in Missouri reservoirs (Knowlton and Jones 1995, Jones et al. 2008b). With 5% cropland and 85% forest cover, the watershed of this impoundment is moderately impacted by human disturbance (Jones et al. 2004, 2008a, 2009), further illustrating inherent temporal variation.

Annual inflow also affects temporal variation. In an extreme example, mean summer TP increased in a large impoundment by an order of magnitude between a drought year and a wet season (18–163 µg/L; Knowlton and Jones 2006a). In another example, summer

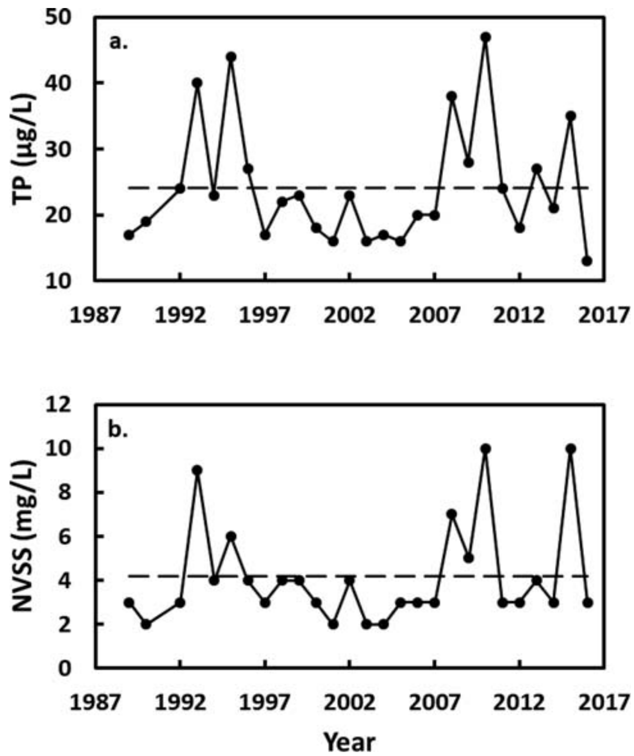

Figure 6. Summer mean values of total phosphorus (TP) and non-volatile suspended solids (NVSS) from Lincoln Lake, Missouri, during 1989–2016 ($n = 27$). Overall mean TP was 23 µg/L and overall mean NVSS was 3.6 mg/L.

mean TP in a hydropower reservoir varied from 12 to 58 µg/L, about half the range of TP found in reservoirs throughout the state (Jones et al. 2008b). Inflow accounted for some 82% of temporal variation of TP in this impoundment ($n = 35$ seasons; JRJ, unpubl. data). A comparison of TP levels in wet and dry years showed, on average, values averaged 43% larger in wet years in 91% of impoundments with agricultural catchments (Jones et al. 2008a), further demonstrating the importance of hydrology on reservoir TP.

Simulations demonstrated temporal variation could mask a gradual doubling of TP over 20 years in Missouri reservoirs (Knowlton and Jones 2006b). With monthly summer sampling, 17 seasons of TP data are required to detect an incremental doubling in TP. This analysis suggest gradual changes in TP will not be stand out against inherent temporal variation in these impoundments.

Assessment of phosphorus abatement

Internal loading: an unmeasured source of variation

Unmeasured in this analysis of factors determining P in reservoirs is an estimate of internal loading (Nürnberg

2009), which likely is a component of residual variation in our analyses. Most Missouri reservoirs stably stratify in early summer concurrent with incipient depletion of dissolved oxygen. Ephemeral secondary stratification is common, and as summer progresses, isotherms below the mixed layer deepen during stratification (Jones et al. 2011). These conditions would promote P movement into the mixed layer and would add to temporal variation. In systems where internal loading is consequential, chemical treatment may be appropriate (Osgood 2017) but challenging, and often longevity is minimally effectual in rapidly flushed systems (Huser et al. 2016). In these cases, the efficacy of P mitigation using chemicals may be increased by considering a range of strategies (Osgood 2017).

Best management practices and land conversion

In landscapes with nonpoint nutrient sources, BMPs are considered practical modifications available to decrease nutrient delivery downstream. It is beyond the scope of this research note to review the types and efficiencies of BMPs, but a recent summary by Osgood (2017) suggests reductions of P load <25% result in slow or no discernable responses in receiving waterbodies. In midcontinent landscapes, reductions of 25% may be beneficial, particularly when seasonal inflows occur prior to summer stratification (Fig. 2), but may be difficult to discern given inherent temporal variation. Problematic is whether conservation measures can be implemented at a sufficient scale and intensity to achieve the large-scale reductions in P loading required to reverse eutrophic conditions, which Osgood (2017) estimates at >80% based on global case studies.

Another consideration is whether BMPs effectively reduce bioavailable forms of P (Dodd and Sharpley 2016). Instrumented watersheds in Missouri showed grass filter strips reduced P loss from cropped watersheds by two-thirds and sediment by ~40%, which supports other findings of grass strips promoting deposition of particulate P (Udawatta et al. 2006, 2011). These deposits may become P sources over time (Dodd and Sharpley 2016). Conservation tillage also lowers sediment and particulate P transport but when coupled with other management practices can increase transmission of soluble P from agricultural fields (Dodd and Sharpley 2016, Jarvie et al. 2017). Reducing sediment load to midcontinent reservoirs may improve light transmission in the water column resulting in increased algal biomass, which would register as increased eutrophication (Hoyer and Jones 1983, Jones and Knowlton 2005a). These examples illustrate the uncertainty associated with BMPs and some unexpected consequences. That said, Osgood (2017) highlights a case where a 50% reduction in external P was achieved with strategic implementation of BMPs with measurable improvements to a mesotrophic lake with a small watershed, requiring an investment of millions of dollars over 20 years.

Our analyses indicate large-scale reductions in cropland would result in disproportional reductions in TP. In Missouri, reducing crop cover from 60% to 30% would decrease TP loading by only 20%, when other factors are held constant (Jones et al. 2008a). This degree of land conversion is impractical on a broad scale. In one case, conservation funds were used to convert about 11% of catchment from mixed agricultural use to grassland and restored prairie, but the benefits were masked by in-reservoir variation (JRJ, unpubl. data).

Concentrated feeding operations

An expanding source of nutrients in the region is litter and liquid waste distributed on fields from concentrated feeding operations (Mallin and Cahoon 2003). Grain imported from outside the watershed supports intensified animal husbandry, and the resulting waste is applied to nearby agricultural land. These fertilizers are potentially lost downstream but also accumulate as legacy deposits, which can be remobilized over time and mask subsequent restoration efforts (Sharpley et al. 2013). About 5% of P experimentally applied to land as poultry litter runs off each year and may continue for decades after applications cease (Sauer et al. 2000, Carpenter 2005). Eutrophication of a midcontinent reservoir from poultry litter has been documented (Cooke et al. 2011, Welch et al. 2011). Soils with litter application in the watershed had P levels double to an order of magnitude greater than soils without litter amendments (Cooke et al. 2011). In another example, 2 Missouri impoundments that historically had dairy barn solids applied to their watersheds have TP levels some 5–10-times the median for the region (Ozark Border; Jones et al. 2008b), with soil P tests ranging from 5 to 10 times background (JRJ, unpubl. data). Also, over time, agricultural pastures receiving wastes from these operations will become a greater source of P and are likely to increase in importance for predicting reservoir nutrients using landscape variables at a large spatial scale (Jones et al. 2009, Knoll et al. 2015). These cases highlight the potential for additional eutrophication from industrialized livestock production, which can be avoided with management practices that match waste applications with agronomic needs or advanced treatment and removal of wastes.

Altering hydrology

Lake restoration typically focuses on reducing external loading, but alternatives have been used. Where possible, increasing the dam height to reduce FR may be a practical approach and draws on theory that FR exerts an asymptotic influence on lake nutrients (Welch and Jacoby 2004). A ~40% decline in summer TP resulted from raising the spillway of a water supply reservoir in Missouri by 1.2 m, which increased volume and reduced FR (Youngsteadt 2005). Similar modifications could improve water quality in reservoirs built with inadequate depth and residence time and benefit numerous basins in the region that have lost storage capacity to sedimentation (deNoyelles and Kastens 2016). Hypothetically, a modest increase in the dam height of a prairie reservoir from 3.5 to 4 m, reducing FR from 1 to 0.6 per year, would result in a 17% reduction in TP (from 52 to 43 µg/L, using equation 5, table 2 in Jones et al. 2008a). Greater modification and inclusion of BMPs would further reduce TP levels and benefit water quality.

Conclusion

Early work by Jones and Bachmann (1978a) concluded that "steps could be taken to reduce nutrient inputs from agricultural watersheds but the probable reductions would largely be ineffective except for the protection of a few individual lakes." That statement was intended to temper expectations for reversing eutrophication in agricultural landscapes and implied that improvements from nonpoint control measures would not likely match reductions realized from wastewater diversion, such as Lake Washington. Cross-system modeling provides a basis for explaining reservoir variation at the landscape level, which accounts for the prevalence of eutrophic conditions in midcontinent impoundments. With all other factors equal, impoundments designed with low FR are desired. In most midcontinent reservoirs, any incremental benefits of BMPs are unlikely to stand out against the backdrop of inherent variation. That said, TP reduction may be consequential when a reduction in FR is coupled with strategic BMP installations. Expansion of industrialized animal production throughout the region suggests legacy P and resulting eutrophication will increase over time unless regulated, making reversal of conditions even more challenging. Essentially, nutrients from confined animal operations are point source applications to nonpoint landscapes (surface disposal). Unlike Hasler's decades-old characterization of lake fertilization from domestic wastewater, land fertilization from animal manure above agronomic requirements cannot be considered inadvertent.

Acknowledgements

We thank the Missouri Department of Natural Resources and Missouri Agricultural Experiment Station for supporting this work. We also recognize input from Anthony Thorpe and scores of student assistants for sample collection and analyses. We appreciate valuable comments from Dick Osgood, of Lake Advocates, on an early draft of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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