When phosphorus (P) enters a lake – by any source or in any form – a large portion of it stays in the lake. For natural lakes, >90 percent retention is common. This excess P builds up in the lake bottom sediments. When the overall accumulation exceeds the burial rates, the pool of sediment P can recycle back into the water in a long-term, self-sustaining cycle – an unwanted gift that keeps on giving.

The phenomenon of internal nutrient loading (INL) has been long recognized. INL’s confounding impacts relative to lake rehabilitation were first recognized with Shagawa Lake, MN. In that case, modeling estimated it would take 80 years for the lake to achieve a 90-percent recovery despite an 80-percent P reduction from wastewater effluent (Cooke et al. 2005).

INL is a significant sustaining factor in many eutrophic or phosphorus-impaired lakes.

With the clean-up of the nation’s sewage-impacted lakes (for example, Lake Washington, WA), the overall lake restoration paradigm shifted to the mitigation of nonpoint phosphorus sources, that is, runoff from a lake’s watershed. In the United States, mitigating eutrophication is driven largely through the administration of the Clean Water Act through the impaired waters designation and implementation of TMDLs (total maximum daily loads).

This shift in emphasis and strategy has largely been ineffective – our lakes are not recovering.

At this time, half (50.1 percent) the nation’s lakes remain eutrophic or hypereutrophic, 27-41 percent of lakes have moderate to high risk of exposure to algal toxins, and from 1972 through 2007, there has been no net change in lake trophic state (51 percent unchanged, 23 percent increased, 26 percent decreased; USEPA 2009).

There are two main reasons for this:
- Watershed management using best management practices (BMPs) is insufficient.
- INL is often a substantial factor.

The math is easy. In a typical case, a P-impairment results from a 10- to 20-fold increase (based on an un-impaired baseline) in P delivery to a lake following a period of agricultural or urban land conversion. Watershed management using BMPs may reduce this P load by 50 percent at best (in practice, this is much less). This leaves the P load at five to ten times over the baseline, meaning the lake impairment is sustained. When INL is involved, it must also be mitigated if the lake is to recover.

**What phosphorus reductions need to occur and from what sources?**

To restore a lake to a mesotrophic or un-impaired condition, phosphorus reductions from both external (watershed) and internal (INL) sources need to occur in most cases.

I have modeled (see Nürnberg 2009) hypothetical situations to illustrate guidelines and limitations of watershed management. Further, I have keyed this model to the watershed:lake surface area ratio. I have assigned moderate rates of phosphorus loading, comparable to suburban development densities (100 mgP\(^\circ\)•year/m\(^2\) or 1.1 pounds•year/acre; see Holdren et al. 2001; Shaver et al. 2007) and moderate rates of INL (6 mg•day/m\(^3\); see Nürnberg 1988). In addition, I evaluated these scenarios for deep, mid-depth, and shallow lakes (Osgood Indices = 11, 7, and 3, respectively) (see Osgood 1988). Using these rates, applied to watershed:lake surface ratios, I estimated the percentage of external phosphorus reduction that would need to occur to achieve a lake phosphorus concentration [TP] of 30 parts per billion (ppb) or µg/L, the threshold for eutrophication. Figure 1 depicts the results.

There are several points to be made.

First, even with moderate intensities of phosphorus loading, substantial external phosphorus reductions are required to restore lakes, except for deep lakes in small watersheds. While beyond the scope of this article, I chose to illustrate the 50-percent watershed phosphorus threshold because in practice, this level of reduction may be achievable in ideal cases. More realistically, 25-percent reductions are the greatest practically attainable levels.

Second, shallow lakes with INL, are not sufficiently responsive to external phosphorus reductions. Even though internal phosphorus mobilization occurs by different mechanisms (turbulent mixing vs. redox mediated mobilization), its impacts are still large. External phosphorus reductions >90 percent are required to restore shallow lakes.

Finally, the watershed:lake surface area ratio can be used as an index to evaluate the potential for watershed management efficacy. Ratios > 5:1 to 10:1 indicate significant watershed management challenges, except for undisturbed watersheds. Watershed:lake surface area ratios from 7 to 10 are considered small (Holdren et al. 2001), so many lakes’ watersheds are apt to be too large for a BMP strategy to be effective.

**How can lake P be effectively restored?**

When INL is in play, it will need to be mitigated. Below (in shaded box), I
present a hypothetical example using the same loading rates (moderate external and internal P loading rates) and model as in the above.

There are several points to be made:

First, INL reductions are sufficient to meet the water quality criteria in the smallest (least impacted) watersheds.

Second, the combination of 25-percent external P reduction and 85-percent internal P reduction was chosen to represent realistic levels of P reductions from external and internal sources using available methods. Water quality criteria can be met using the combination strategy for somewhat more impacted deeper lakes.

Finally, for the most impacted lakes, extraordinary strategies will be required. Such chemical or engineering strategies may include intercepting runoff and treating it with alum, as is done in many Florida lakes (Harper 2013). Also, periodic water column phosphorus stripping treatments may be effective.

Summary

INL presents management challenges for restoring phosphorus-impaired lakes. The modeling presented here is meant as illustrative of a wide range of situations. This assessment can be useful for broad-scale policy and planning, but is not a substitute for evaluating each lake and watershed to be managed. Evaluating specific cases requires site-specific modeling and evaluation.

The overall lack of lake improvements in the United States suggests our reliance on watershed management is an incomplete or insufficient approach.

One explanation is the belief that external (watershed) phosphorus is the ultimate offending source and therefore it is most appropriate (at least philosophically) to address that source first and wait for a long enough time (but how long? Rissman and Carpenter [2015] estimated 250 years for Lake Mendota). In this context, INL has been referred to as a “symptom,” implying it is a lesser or lower priority target for management.

Internally supplied phosphorus is no more a “symptom” then nonpoint source phosphorus is a “symptom” of excessive land alteration. Unless we are willing or able to reverse long-standing land uses on large scales, it is unproductive to apply this argument.

We must stop calling internally supplied phosphorus a symptom – it is an equal part of the eutrophication syndrome as other phosphorus sources and should not be relegated to an afterthought.

As illustrated here, both external and internal phosphorus requires mitigation (in most cases) if we are to achieve lake water quality goals. Furthermore, our management strategies ought to be expanded to include all feasible and effective phosphorus reductions methods,
evaluated based on feasibility, efficacy, costs and sustainability.

References


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