Water quality implications from three decades of phosphorus loads and trophic dynamics in the Yahara chain of lakes

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Abstract

Trophic responses to phosphorus (P) loads spanning 29–33 years were assessed for the eutrophic Yahara chain of lakes: Mendota (area = 39.6 km², mean depth = 12.7 m, flushing rate = 0.23 yr⁻¹); Monona (13.7 km², 8.3 m, 1.3 yr⁻¹); Waubesa (8.5 km², 4.7 m, 4.3 yr⁻¹); and Kegonsa (13.0 km², 5.1 m, 3.0 yr⁻¹). During extended drought periods with low P loads, summer (Jul–Aug) total P (TP) concentrations declined substantially in all 4 lakes, with Mendota achieving mesotrophic conditions (<0.024 mg L⁻¹). In years when P loads were high due to major runoff events, summer TP in the lakes was high (especially in shallower Waubesa and Kegonsa); in some summers dissolved inorganic P was elevated, indicating algae growth was not P limited. Summer TP returned to normal levels following both low and high load years, signifying the lakes were responsive to P load changes. The proportion of P input loads passed via a lake’s outlet to the next lake downstream increased as flushing rates increased. Because Monona, Waubesa, and Kegonsa received 60, 83, and 76% of their surface water P load from the respective upstream lake’s outlet, reducing P loads in Mendota’s large watershed was predicted to produce significant water quality benefits downstream. Modeling indicated a significant grazing effect of Daphnia on summer TP and Secchi transparency readings for Mendota and Monona. Finally, using drought loads as targets, our study established P loading reductions needed to improve water quality in all 4 Yahara lakes.

Key words: agricultural runoff, Daphnia, Lake Mendota, nonpoint pollution, phosphorus loads, Secchi disk, total phosphorus, Yahara lakes

Introduction

Eutrophication of lakes worldwide is linked to over-fertilization by phosphorus (P), which stimulates blooms of blue-green algae (Sas 1989, Schindler 2006, Smith et al. 2006, Carpenter 2008). The Yahara River chain of 4 lakes (Mendota, Monona, Waubesa, and Kegonsa in downstream order; Fig. 1) near Madison, Wisconsin, USA, exemplifies those eutrophication problems because blue-green algal blooms have been legion for more than a century. The first problems from blue-green algae were in the lower 3 Yahara lakes, which received Madison’s partially treated wastewater until the effluent was diverted in 1958 (Lathrop 2007). Mendota’s algal bloom problems began shortly after World War II when wastewater inputs of P from upstream communities increased coincident with an increase in agricultural and urban nonpoint pollution from Mendota’s watershed (Lathrop 1992, Lathrop 2007, Carpenter et al. 2006). After upstream community wastewater discharges to Mendota ended in 1971, agricultural and urban runoff produced even higher levels of P in the lake in subsequent years.

Nonpoint pollution reduction programs first began in the 1970s and continue today, with little perceived change in the frequency or severity of blue-green algal blooms in Mendota or the other 3 Yahara lakes (Lathrop et al. 1998, Carpenter et al. 2006, Lathrop 2007). However, a heightened awareness of injurious and potentially deadly
Toxins associated with blue-green algae has intensified governmental and citizen efforts to reduce P inputs to the Yahara lakes as the primary mechanism to improve water quality. The Yahara CLEAN Project was launched in 2008 as a joint partnership to achieve that end.

To help focus these lake clean-up efforts, we developed and analyzed long-term P loading and lake response data to estimate the effects of specific P loading reduction targets for the 4 Yahara lakes. Modeling also indicated an important role for algal grazing by *Daphnia* in these summer trophic state determinations and helped support our load reduction targets considering potential food web alterations expected to result from invasive species. Finally, our analyses quantified the benefit of reducing P loads to upstream lakes because those reductions cascade to downstream lakes via decreased loads in upstream lake outlet waters. Analyses that examine the response of lake trophic conditions to external P loading have been widely applied to individual lakes for decades, but fewer studies have analyzed lake loading relationships in chains of lakes (Elser and Kimmel 1985, Choulik and Moore 1992, Hillbricht-Ilkowska 2002, Epstein et al. 2013). Our study has proved important for local lake P control efforts, but our approach is also applicable to other lake systems.

**Methods and approaches**

**Phosphorus loadings**

**Lake Mendota:** We developed 33 years of annual P loads to Lake Mendota for 1976 through 2008 using approaches updated from previous analyses (Lathrop et al. 1998, Carpenter and Lathrop 2008). Our new lake response modeling used an annual loading time step from 1 November of the previous year through 31 October of the stated year instead of a mid-April annual time step used in
our earlier analyses. This new loading time step allowed the lake’s P status (water column P concentration or mass) on 1 November of each year (i.e., after fall turnover commenced) to be used as a hindcast predictor of each summer’s water quality and eliminated the problem of loads before and after mid-April falling into different load years. Thus, annual loads using the 1 November time step were more precisely linked to each summer’s water quality. For our lake response modeling, in-lake water quality data were available for 29–33 years of annual P loads.

P loads for rural and urban subbasins (hydrologic units) in all 4 Yahara lake drainage basins were estimated by Montgomery Associates Resource Solutions using the 2005 version of the SWAT model (Nietsch et al. 2005, Gassman et al. 2007), the latest model version available at the time of the consulting firm’s contract work. The popular, nationally used model proved an effective inventory tool for land use practices, potential pollution sources, and subwatershed areas for the Yahara lakes. Using local daily precipitation data and land use information provided by Dane County and the City of Madison, the model predicted monthly water export and sediment and P loads for each subbasin during the 33 loading study years (1976–2008).

We did not use the P-loading data predicted by SWAT 2005 for Lake Mendota’s rural subwatersheds because the model did not have subroutines to accurately predict P loads during late-winter runoff events when the ground is frozen and winter spreading of manure occurs, a widespread practice in the Mendota watershed with a large number of dairy operations. Instead, we developed P loads based on 2 of Mendota’s subwatershed tributaries (Yahara River and Pheasant Branch) that had long-term US Geological Survey (USGS) monitoring data for P loads. Previous analyses indicated the January–March runoff period represented 43–48% of the long-term annual P load in these 2 subwatersheds (Lathrop 2007).

Similar to our earlier analyses of P loads in the Lake Mendota watershed, we used monthly monitored subwatershed loads to predict monthly P loads in other subwatersheds (Sixmile Creek and Token Creek) based on predictive relationships developed from more extensive monitoring data available for 1976–1980 (Lathrop 1998). While we recognize that changing land management practices within each subwatershed could alter these predictive relationships over time, late-winter runoff events and seasonal droughts would be systemic throughout the lake’s entire watershed. For rural areas without historical monitoring data, P loads were extrapolated from each year’s monitored subwatershed loads.

We computed P loads for urban storm sewer basins draining directly to Lake Mendota using water flow volumes predicted by SWAT for the 33 loading years for each basin, multiplied by each basin’s P export coefficient computed by SLAMM modeling (Pitt and Voorhees 2002) performed by USGS for the City of Madison in the early 2000s. A comparison of monthly SWAT modeling results with USGS long-term flow monitoring data for Mendota’s Spring Harbor storm sewer basin indicated that SWAT produced reliable annual flow volumes for urban basins. The SLAMM modeling provided P loading and water volume data for each urban basin using “average year” precipitation data for 1981 and 2000 land use data to run the model. From the SLAMM modeling results, an average P concentration for each urban basin was then computed that reflected the characteristics of each basin. We then calculated P loads for each urban basin for all 33 loading years in our analyses by multiplying SWAT’s predicted annual water volumes times each basin’s average P concentration. While this approach did not account for any urban land use changes during 1976–2008, the approach did incorporate yearly variations in runoff volumes used in calculating the annual urban P loads.

Outlet P loads for Lake Mendota were computed by multiplying discharge volumes for the lake outlet times mid-lake surface water P concentration data. Daily outlet flows were calculated from equations using gate and lock opening records for 1976–1997 (Lathrop et al. 1998). Since 2003, daily flows have been measured by USGS in the Yahara River downstream of the lake outlet. For 1998–2002, monthly outlet flow volumes were predicted from Yahara River flows at Waubesa’s outlet where a long-term USGS gauging station is located. Lake P concentration data that corresponded to the daily or monthly outlet flows were interpolated from surface P concentrations measured in samples collected generally biweekly during spring and summer, every 2–4 weeks during fall, and at least once during winter when the lakes were ice covered.

**Lake Monona:** The largest portion of the annual P load to Lake Monona came from the outlet of upstream Lake Mendota. For the mostly urban land draining directly to Monona, we computed P loads using the same methods as for Mendota’s urban basins: the SLAMM-derived P export concentration for each urban basin was multiplied by the SWAT-derived water discharge volumes predicted for each year during 1976–2008. Because these were end-of-pipe P loading estimates, however, P loads to all urban basins discharging to Lake Wingra, a shallow 1.3 km² lake in the western part of Monona’s direct drainage basin, were attenuated before the water entered Monona. To adjust for this, we multiplied P concentration data available for Lake Wingra times the SWAT-derived annual water volumes for all urban basins discharging directly to Wingra to produce a more realistic estimate of annual P loads leaving Wingra and entering Monona from the west end of its urban
drainage basin. No other adjustments were made for urban P loads entering Monona, although a limited amount of monitoring data from 1976 for the Starkweather Creek subwatershed on Monona’s northeast side indicated some attenuation of P loads may be occurring in that relatively flat subwatershed.

We computed Monona’s annual outlet P loads for 1976–2008 by multiplying monthly flow volume estimates times interpolated lake P concentration data, as for Mendota. Monthly flow volumes were predicted from Lake Waubesa outlet flow records using a relationship developed from historical monthly flow data for the outlet of Monona.

**Lake Waubesa:** Outlet P loads from Lake Monona constituted the largest P-loading source to Lake Waubesa. To compute Waubesa’s direct drainage P loads for 1976–2008, we used SWAT P loading results because no nearby subwatershed monitoring data were available. The SWAT loading bias for winter manure runoff as described for Mendota was expected to be less important for Waubesa because watershed inventory data indicated that little manure is produced in Waubesa’s direct drainage area. Additionally, even with a large error in the P loading estimates for Waubesa’s direct drainage area, its P load was relatively small compared to the river load coming from upstream Lake Monona. For Waubesa’s outlet P loads, we multiplied USGS monitored daily discharge volumes times interpolated lake P concentration data for 1980–2008. We did not compute Waubesa outlet loads prior to 1980 due to the lack of reliable lake P data.

**Lake Kegonsa:** Outlet P loads from upstream Lake Waubesa constituted the largest P-loading source to Lake Kegonsa during 1980–2008. We calculated the direct drainage loads to Kegonsa for those same years using the SWAT modeling results, as for Waubesa. Outlet P loads for Kegonsa were based on interpolated lake P concentration data for 1980–2008 and monthly flow volumes predicted from Waubesa outlet flow records.

**Other P loading sources:** In addition to P loads entering the 4 lakes via streams and storm sewers, P can also enter via dry fallout and precipitation directly on the lake surfaces, and from groundwater inputs, with dry fallout being the most important of the 3 sources. Early estimates for these sources were developed for Lake Mendota (Lathrop 1979) and treated as a constant annual input of P in our loading analyses. We applied estimates for these sources to the lower Yahara lakes based on a unit lake surface area conversion from Mendota’s estimate (excluding groundwater, which has much less inflow to the lower Yahara lakes).

**Volumetric P loads:** Because the 4 Yahara lakes have widely differing surface areas and water depths and volumes (Table 1), we also calculated volumetric P loads \((\text{g m}^{-3} \text{yr}^{-1})\) by dividing each lake’s annual load by that lake’s water volume. This allowed more direct comparisons of the magnitude of annual P loads each lake received during 1976–2008.

**Lake outlet pass-through load factors**

One important set of analyses estimated the P load reductions that would cascade to a downstream lake following upstream lake P-load reductions. For Mendota, these reductions would come from watershed management practices; for the lower 3 Yahara lakes, P loading reductions to each lake could result from practices installed in the direct drainage basin or from less P leaving the upstream lake’s outlet.

To determine these lake outlet “pass-through” factors, we plotted the annual outlet P loads versus the annual total input P loads for each lake and verified that all the lake input:outlet relationships were linear. We then developed simple linear regression equations where the regression slope coefficient for each lake’s input:outlet relationship was that lake’s pass-through factor. Thus, for a P load reduction realized for a given lake, a percentage of that load reduction would result in a reduction in P leaving the lake’s outlet to provide downstream water quality benefits.

**In-lake water quality**

To help set summertime water quality goals for the Yahara lakes, we used Carlson’s (1977) Trophic State Index (TSI) in which separate equations for in-lake total phosphorus (TP) concentrations and Secchi disk transparency readings allowed the boundary between mesotrophy and eutrophy (TSI = 50) to be computed. These boundaries corresponded to TP = 0.024 mg L\(^{-1}\) and to Secchi transparency = 2.0 m; thus, when the lakes experienced summer TP concentrations <0.024 mg L\(^{-1}\) or Secchi transparencies >2.0 m, then mesotrophic conditions occurred as defined by the separate indices. When the lakes had TP >0.024 mg L\(^{-1}\) or Secchi transparencies <2.0 m, the lakes had eutrophic (or in some cases hypereutrophic) conditions. Because the TSI values for TP and Secchi were independently derived, the 2 indices did not always agree on a lake’s trophic state on any given sampling date or time period. For example, a Secchi-TSI could indicate the lake was mesotrophic while the TP-TSI could indicate the lake was eutrophic.

To portray long-term water quality trends in the 4 Yahara lakes, we compiled available long-term Secchi disk readings and surface water TP concentrations for the summer months when algal blooms are most problematic.
Reliable TP concentration data have been regularly collected in the lakes since 1980 (Lathrop 2007); Secchi disk transparency data have been routinely collected since 1976 in Mendota and Monona, and since 1980 in Waubesa and Kegonsa. All data are accessible through the North-Temperate Lakes Long-Term Ecological Research project (http://lter.limnology.wisc.edu). Because the Yahara lakes all exhibited a strong clear-water phase during late spring and early summer (i.e., Jun), we standardized our summer lake water quality dataset by using data collected between 30 June and 7 September to represent “July–August” summer conditions. We chose this date range to ensure comparable data were analyzed each year. Results are presented through 2012 to detect more recent water quality trends.

Water quality variables such as summer surface TP and Secchi transparency are highly variable from day to day in eutrophic lakes; the Yahara lakes are no exception. Phosphorus load and algal grazing by zooplankton are important variables that control year-to-year water quality conditions, but day-to-day variability can be high even at fixed conditions of P load and grazing. To address this variability, we computed probabilities of meeting the water quality goal for mesotrophy using both the TP and Secchi TSI indices. Thus, our lake response modeling focuses on the probability of mesotrophy occurring in the lakes (i.e., the probability of having TP <0.024 mg/L or Secchi transparency >2.0 m on any given Jul–Aug day).

**Phosphorus load simulation:** Our modeling process involved first simulating the probability distribution of P loads for a given change in mean annual loading, and then simulating the probability distribution of water quality conditional on the P load distribution. The approach is similar to that used by Lathrop et al. (1998); however, here we employ a more extensive time series and predict summer surface-water TP and Secchi transparency instead of blue-green algal biomass as the water quality responses.

To generate simulated P load distributions, we first fit autoregressive models to the observed time series for annual P loads to lakes Mendota and Monona. We then computed predicted loads using the Bayesian posterior distribution (Gelman et al. 2004), a Student t-distribution similar to the distribution of predictions from an ordinary linear regression (Gelman et al. 2005). Simulated load distributions were random samples from these Bayesian posterior distributions. Statistical moments (mean, variance, range, autocorrelation) were similar for the predicted distributions and the actual observed distributions.

To simulate different loading conditions, we rescaled the predicted load distributions so that the mean was a specified multiplier of the observed mean for 1976–2008 with a range of multipliers from 0.2 to 2.0, with increments of 0.1. For example, when the load multiplier is 1.0 (corresponding to 0% change from current conditions), the simulated loads match the mean of the observed loads. When the load multiplier is 2.0, the simulated loads have a mean twice as large as the observed loads. When the load multiplier is 0.5, the simulated loads have a mean half (or 50%) of the observed loads. For each load multiplier, we computed 5000 years of simulated P loads. These values were then used as input to compute distributions of lake water quality variables.

**Lake water quality simulation:** We computed regression models to predict surface water TP concentrations and Secchi transparency for lakes Mendota and Monona from P load and an algal-grazing index of the dominant *Daphnia* species of zooplankton present in the lake each spring–summer (Lathrop et al. 1996). The grazing index was 1 if the larger-bodied *Daphnia pulex* was the dominant grazer that year, and 0 if the smaller-bodied *Daphnia galeata mendotae* was the dominant grazer. *D. pulex* is an effective algal grazer known to increase water clarity in lakes (Kasprzak et al. 1999, Lathrop et al. 1999). Each regression model yields a posterior probability distribution for surface water TP or Secchi transparency given the distribution of annual P loads and presence or absence of *D. pulex*. This posterior distribution is a Student t-distribution similar to the distribution of predictions from a linear regression (Gelman et al. 2004).

### Table 1. Physical characteristics of the Yahara lakes.

<table>
<thead>
<tr>
<th></th>
<th>Mendota</th>
<th>Monona</th>
<th>Waubesa</th>
<th>Kegonsa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drainage area (km²)</td>
<td>553</td>
<td>119</td>
<td>124</td>
<td>155</td>
</tr>
<tr>
<td>Lake area (km²)</td>
<td>39.6</td>
<td>13.7</td>
<td>8.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Total watershed area (km²)</td>
<td>593</td>
<td>725</td>
<td>858</td>
<td>1026</td>
</tr>
<tr>
<td>Maximum lake depth (m)</td>
<td>25.3</td>
<td>22.6</td>
<td>11.3</td>
<td>9.8</td>
</tr>
<tr>
<td>Mean lake depth (m)</td>
<td>12.7</td>
<td>8.3</td>
<td>4.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Lake volume (m³ × 10⁶)</td>
<td>505</td>
<td>110</td>
<td>39.5</td>
<td>66.8</td>
</tr>
<tr>
<td>Mean flushing rate (yr⁻¹)</td>
<td>0.23</td>
<td>1.3</td>
<td>4.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Given a sample of simulated P loads and the presence or absence of *D. pulicaria*, we computed a random sample of water quality using the posterior distribution of the water quality regression. By integrating Bayesian posterior distributions for surface water TP and Secchi transparency, we computed the probabilities of TP <0.024 mg L\(^{-1}\) and Secchi transparency >2.0 m (i.e., mesotrophic conditions) for each value of the P load multiplier (or percent change in mean annual P load) with and without dominance by *D. pulicaria*. We interpreted these results as the probability of mesotrophic conditions for each scenario of P load and grazer dominance in lakes Mendota and Monona.

We also conducted similar modeling analyses for lakes Waubesa and Kegonsa, but results are not reported here because lake TP and Secchi transparency were not responsive to P loads for many reasons. First, the volumetric P loads for those lakes were considerably larger than for Mendota and Monona, which may explain why Waubesa and Kegonsa had elevated dissolved reactive (inorganic) P concentrations (DRP) during many summers (Lathrop 2007). Elevated DRP is an indicator that algal growth was not limited by P; thus, water quality in the lower 2 Yahara lakes during 1980–2008 was unresponsive to variations in annual P loads because the loads in most years were so large. In addition, the lower 2 lakes are relatively shallow (compared to Mendota and Monona) and therefore are subject to high internal recycling rates of P from the bottom sediments throughout the summer. Furthermore, *Daphnia* data were not available to compute a grazing index for Waubesa and Kegonsa; therefore, any variance due to grazing could not be accounted for in regression models.

**Results**

**P loads to the Yahara lakes**

**Trends in Mendota’s monitored subwatershed P loads:** The most reliable indicators of trends in annual P load to Lake Mendota were from its monitored subwatersheds where daily P loads have been calculated since 1976 for Pheasant Branch, and for 1976–1980 and since 1990 for the Yahara River (Fig. 2). Annual P loads (Nov–Oct) in both subwatersheds exhibited considerable year-to-year variation that included 2-year droughts (1987–1988, 2002–2003, 2011–2012) and years of extreme runoff events causing massive flooding (1993, 2008) as well as years with significant January–March runoff loadings (1993, 1994, 1997, 2005, 2009; Lathrop 2007). We included available loading data for 2009–2012 to indicate more recent P loading trends. From 1976 through 2012, the annual P loads varied considerably in the 2 monitored tributaries to Lake Mendota. Since 1990 when both sub-watersheds have been monitored continuously, Pheasant Branch P loads trended slightly downward, possibly due to the construction of an in-stream sedimentation pond in 2001 (Gebert et al. 2012), while the Yahara River P loads exhibited no changing trend.

**Outlet P loads:** The annual outlet P loads for all 4 Yahara lakes were highly correlated and exhibited significant interannual variability (Fig. 3). In general, because of greater river flows sequentially down the Yahara River chain, the outlet P loads for the lake immediately downstream were slightly higher than for the upstream lake. In some years, Kegonsa’s outlet P load was notably higher than the other lake outlet loads, which reflected Kegonsa’s higher outlet flow rates combined with its usually highest lake P concentrations. The outlet P loads for the 4 lakes also mirrored the periods of major droughts and extreme runoff events in the long-term record. For the 1987–1988 drought, the full effect on outlet P loads was delayed to 1988–1989 due to less water leaving Mendota (and the other lakes) at the end of the drought. The 2-year drought of 2002–2003 also produced relatively low outlet P loads for the lakes in 2003; however, outlet P loads for years preceding that drought were generally much higher than during years preceding the late 1980s drought.

**Volumetric P loads:** The long-term record of volumetric annual P loads for each of the 4 Yahara lakes were plotted as a set of probability distributions (Fig. 4). For each lake, the distribution of volumetric annual loads is skewed due to a few extremely high load years (e.g., 1993 and 2008). The most important finding of this analysis is that the P loads to each lake were substantially larger with greater load modes (and means) and variance for each successive downstream lake; Waubesa’s and Kegonsa’s load distributions were relatively similar but had large modes and variance compared with Mendota’s loads, with Monona being intermediate. Even comparing Mendota’s and Monona’s volumetric annual P loading distributions for 1976–2008, the P loads to Monona were higher than any loads calculated for Lake Mendota except for the most extreme loading years of 1993 and 2008. Conversely, the drought P loads to Mendota were lower than any loads recorded for Monona. We believe these volumetric P loading comparisons help explain why the lower lakes, especially Waubesa and Kegonsa, were less responsive to variations in P loading during the long-term record. The quantity of P flowing into those lakes was probably so large that algae growth was not P limited during many summers.

**Average P loads for the Yahara lakes:** Mendota had the highest average input load followed by Monona, Kegonsa,
and Waubesa (Table 2); however, the importance of the river load from the upstream lake was evident for the lower 3 Yahara lakes. Excluding dry fallout and other minor sources of P load, Mendota’s outlet P load constituted 60% of Monona’s total surface water input load (outlet plus direct drainage loads). For Waubesa, the upstream outlet river load was 83% of the combined surface water sources; for Kegonsa, the river load was 76% of the combined sources.

**Lake outlet pass-through load factors**

All input:outlet P load relationships for the 4 Yahara lakes were approximately linear, although individual lakes had different regression slope coefficients or outlet pass-through factors (Fig. 5; Table 2). Thus, a percentage of the P loading reduction realized by implementing effective land management practices in the direct drainage basin of a given lake is predicted to occur in that lake’s outlet P load flowing to the next lake downstream. For P load reductions to Lake Mendota, the reduced P load cascades to all 3 lower Yahara lakes. For example, using our empirically derived pass-through factors, a 10,000 kg reduction in P load to Mendota on average is predicted to produce a P load reduction of 2650 kg to Monona (10,000 kg × 0.265). That P load reduction to Monona is predicted to result in a 1550 kg load reduction to Waubesa (2650 kg × 0.586), and in turn a 1450 kg reduction to Kegonsa (1550 kg × 0.935). Kegonsa’s outlet P load to the lower Yahara River is also predicted to decrease by 1130 kg (1450 kg × 0.779). These P load reductions are averages at steady-state; in some years the pass-through benefits will be larger and in other years they will be smaller. Nonetheless, the average steady-state reductions are instructive and demonstrate the pass-through benefits of improving upstream water quality.

As expected, the outlet pass-through load factors were inversely related in ranked order to each lake’s long-term mean flushing rate. Thus, Lake Mendota with the slowest flushing rate (0.23 yr⁻¹) retained the most P entering the lake each year. Lake Waubesa with the fastest flushing rate (4.3 yr⁻¹) had relatively little P retained in the lake. Lakes Monona and Kegonsa with flushing rates of 1.3 and 3.0 yr⁻¹, respectively, corresponded in similar order to the amount of P retained in the 4 lakes.

**Summer lake water quality**

Analyses of summer water quality conditions represented July and August when blue-green algal blooms were the most troublesome during the summer recreation season. Using both TP and Secchi TSI indicators of July–August water quality, Mendota and Monona generally exhibited...
eutrophic conditions while Waubesa and Kegonsa exhibited highly eutrophic conditions. Median TP concentrations of all July–August median values for 1980–2012 in the 4 Yahara lakes were: Mendota (0.032 mg L\(^{-1}\)), Monona (0.034 mg L\(^{-1}\)), Waubesa (0.064 mg L\(^{-1}\)), and Kegonsa (0.077 mg L\(^{-1}\)). Median July–August Secchi disk readings were: Mendota (1.9 m), Monona (1.6 m), Waubesa (0.9 m), and Kegonsa (0.9 m).

Each year’s median July–August TP concentrations for 1980–2012 was highly correlated for Mendota and Monona and for Waubesa and Kegonsa (Fig. 6). While Mendota and Monona often had median TP concentrations well into the eutrophic TP-TSI region, TP was low enough in some summers to reach mesotrophic conditions (<0.024 mg L\(^{-1}\)). Both lakes notably exhibited mesotrophic TP conditions in 1988 in response to the 2-year drought. Although summer TP concentrations in Waubesa and Kegonsa were much higher than in Mendota and Monona, TP dropped close to the mesotrophic boundary in response to the late 1980s drought. Conversely, when the lakes experienced extreme P loads (e.g., 1993 and 2008), July–August TP concentrations returned to more normal levels in 1–2 years when loads declined.

In summers when TP concentrations were high, DRP concentrations were often well above analytical detection, especially in Waubesa and Kegonsa, but also occasionally in the deeper lakes (Fig. 7). Thus, during summers when TP was high due to high P loadings (external and internal), algal growth was likely not limited by P because the turnover rate of DRP would not have been as rapid as when DRP was undetectable; DRP-starved algae would have removed it as fast as it became available. This finding was in contrast to other seasons when DRP has been high in the Yahara lakes (Lathrop 2007, Hoffman et al. 2013).

July–August TP concentrations during 1980–2012 suggested a declining trend in TP had occurred, with the greatest decline in Mendota and the least in Kegonsa,

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Fig. 5. Annual outlet P loads vs. annual P input loads for each of the 4 Yahara lakes. Each lake’s outlet pass-through loading factor is the slope of the linear regression derived from each set of P loads. Mendota and Monona analyses are from 1976–2008 annual loading data; Waubesa and Kegonsa analyses are from 1980–2008 data.
but the trends were not statistically significant due to the high annual variability in TP. While in-lake water quality conditions exhibited the same general trend as watershed P loadings to the lakes during this same time period, we believe the relatively rapid TP response of the lakes (including Mendota) to extremely high or low P loads provides strong evidence that the lakes would respond quickly to major P load reductions.

Median July–August Secchi disk transparency readings were highly variable for Mendota and to some extent for Monona (Fig. 8); Secchi readings were significantly lower with relatively little variability for much more eutrophic Waubesa and Kegonsa. For Mendota, median Secchi readings were in the mesotrophic TSI condition for almost half the years. Monona exhibited mesotrophic Secchi conditions during just 3 summers while Waubesa and Kegonsa did not approach the mesotrophic Secchi boundary during the study period. Mendota and Monona’s greatest Secchi readings during 1976–2012 occurred in 1988 in association with the 2-year drought.

Lake response modeling

Lake Mendota: Our modeling results indicated that the probability of July–August days with mesotrophic water quality conditions in Lake Mendota would increase if the average distribution of P loads to the lake were to decline, although the results were different for the TP (<0.024 mg L\(^{-1}\)) and Secchi (>2.0 m) TSIs (Fig. 9 and 10). Our results also indicated that food web dynamics that affect algal grazing by *Daphnia* zooplankton had a strong influence on the probability of mesotrophic conditions in Lake Mendota.

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Table 2. Summary of annual input and outlet P loads for the 4 Yahara lakes for 1976–2008, including average P loads during late 1980s drought, outlet P loads as proportion of P input loads, P load reduction targets, and 50% P load reduction scenario for the 4 lakes.

<table>
<thead>
<tr>
<th></th>
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<th>Kegonsa</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P Load Summary:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-term average P load entering lake from all sources (kg yr(^{-1}))(^{2})</td>
<td>33,400</td>
<td>20,000</td>
<td>13,300</td>
<td>17,700</td>
</tr>
<tr>
<td>Average load entering lake from direct drainage sources (kg yr(^{-1}))</td>
<td>29,600</td>
<td>7500</td>
<td>2100</td>
<td>4000</td>
</tr>
<tr>
<td>Average load entering lake from upstream lake outlet (kg yr(^{-1}))</td>
<td>–</td>
<td>11,400</td>
<td>10,400</td>
<td>12,500</td>
</tr>
<tr>
<td>Load estimate from other sources (kg yr(^{-1}))(^{3})</td>
<td>3800</td>
<td>1100</td>
<td>700</td>
<td>1100</td>
</tr>
<tr>
<td>Average load leaving lake outlet (kg yr(^{-1}))</td>
<td>11,400</td>
<td>10,400</td>
<td>12,500</td>
<td>15,200</td>
</tr>
<tr>
<td>Lake outlet load as proportion of total input load(^{4})</td>
<td>0.265</td>
<td>0.586</td>
<td>0.935</td>
<td>0.779</td>
</tr>
<tr>
<td>Average total input load during late 1980’s drought (kg yr(^{-1}))(^{5})</td>
<td>17,400</td>
<td>11,700</td>
<td>6800</td>
<td>7100</td>
</tr>
<tr>
<td>Average P load reduction needed to meet drought target load (kg yr(^{-1}))</td>
<td>16,000</td>
<td>8300</td>
<td>6500</td>
<td>10,600</td>
</tr>
<tr>
<td>Target load reduction as percent of all loading sources</td>
<td>48%</td>
<td>42%</td>
<td>49%</td>
<td>60%</td>
</tr>
<tr>
<td>Target load reduction as percent of direct drainage load sources</td>
<td>54%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>P Load Reduction Scenario:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% load reduction from direct drainage sources to lake (kg yr(^{-1}))</td>
<td>14,800</td>
<td>3750</td>
<td>1050</td>
<td>2000</td>
</tr>
<tr>
<td>Load reduction passed through from upstream lake reduction (kg yr(^{-1}))(^{6})</td>
<td>–</td>
<td>3920</td>
<td>4490</td>
<td>5180</td>
</tr>
<tr>
<td>Total load reduction to lake (kg yr(^{-1}))</td>
<td>14,800</td>
<td>7670</td>
<td>5540</td>
<td>7180</td>
</tr>
<tr>
<td>Total load reduction as percent of load reduction needed to meet drought target</td>
<td>93%</td>
<td>92%</td>
<td>85%</td>
<td>68%</td>
</tr>
</tbody>
</table>

\(^{1}\)Waubesa outlet P load and all Kegonsa P loads are for 1980–2008.

\(^{2}\)Long-term average P load to Mendota is 34,500 kg yr\(^{-1}\) if a 1984 fertilizer spill of 4000 kg P in the lake’s watershed is included in average.

\(^{3}\)Other P sources include previously derived average estimates for dry fallout and precipitation (minor). For Mendota, the average estimate for other sources also includes a small P input from groundwater; the 1984 fertilizer spill in the lake’s watershed is excluded in the average estimate.

\(^{4}\)Proportion is slope coefficient of linear regression of each lake’s outlet load versus total input load for all loading years.


\(^{6}\)Pass-through P load reduction is total load reduction to upstream lake multiplied by that lake’s outlet:input load proportion.
Fig. 6. Total P concentrations in the surface waters of lakes plotted as the median of each year’s July–August summer values during 1980–2012. TP < 0.024 mg L\(^{-1}\) signifies mesotrophy; TP > 0.024 mg L\(^{-1}\) signifies eutrophy: (a) lakes Mendota and Monona; (b) lakes Waubesa and Kegonsa.

Fig. 7. Median summer TP vs. median summer dissolved reactive P (DRP) for the 4 Yahara lakes, 1980–2008.

Under current loading conditions, combined with grazer dominance of the large-bodied \(D.\) pulicaria grazer, the probability of lake TP in the mesotrophic state was slightly less than 0.2, or almost 2 of 10 July–August days on average over many years (Fig. 9). If average future P loads were reduced by 50% with the same grazer dominance, then the probability of mesotrophy during July–August was predicted to be almost 4 of 10 days using the TP-TSI indicator. Conversely, if average future P loads substantially increased, then the lake would exhibit eutrophic conditions on most July–August days.

The importance of algal grazing by \(Daphnia\) was identified in our modeling results for Lake Mendota. Prior studies indicated that when \(D.\) pulicaria was effectively eliminated in a particular year due to predation by large densities of planktivorous fish, then the lake was only populated for short periods in late spring by the smaller-bodied \(D.\) galeata mendotae, a zooplankton species that significantly reduced grazing pressure on algae (Lathrop et al. 1996, 1999, 2002). Thus, under current P load conditions and without the presence of the large grazer, the probability of lake TP being in the mesotrophic state is only about 0.05 (i.e., 1 of 20 days) on average over many summers (Fig. 9). Under these same reduced algal grazer conditions but with a 50% P load reduction, the TP mesotrophic probability increases to about 0.15 (i.e., 3 of 20 days), which is close to the probability under the current distribution of P loads with the large grazer present (i.e., 0.2). In other words, our TP-TSI modeling results indicate that a 50% P load reduction could be negated by a food web shift causing the loss of the large-bodied \(D.\) pulicaria grazer in the lake.

Our modeling results for the Secchi-TSI indicate that Lake Mendota was mesotrophic 6 of 10 summer days on
Lake Monona: Modeling results for both TP and Secchi TSI indicators of mesotrophy in Lake Monona were generally similar to results for Lake Mendota with some important differences (Fig. 11 and 12). Monona’s TP-TSI probability of mesotrophy is predicted to increase from 0.2 to 0.3 (i.e., from 2 to 3 of 10 days) with an average P load reduction of 50% from current loads when the large-bodied Daphnia pulicaria is present; the probability increases from 0.1 to 0.2 when the large Daphnia grazer is absent (Fig. 11). For the Secchi-TSI indicator, a 50% P load reduction is predicted to increase mesotrophy probabilities from about 0.35 to 0.45 when the large grazer is present, and from about 0.25 to 0.35 when the large grazer is absent (Fig. 12). Thus, modeling results for both TSI indicators suggest a 50% P load reduction would only produce a net gain of about 1 of 10 days of mesotrophy in Lake Monona for either algal grazing condition.

Drought P loading targets

Because all 4 Yahara lakes responded with dramatically reduced in-lake P concentrations during the late 1980s drought, we believe the average annual P loads estimated for that drought period provide a good P loading target for management efforts (Table 2). The drought loading targets can then be used to determine what percentage reduction in average P load is needed from each lake’s total load, as well as direct drainage sources for Mendota. For Mendota, average P loads would need to be reduced by 48% based on all P loading sources, or 54% based on direct drainage sources, to meet the drought loading target. Similarly, the P load reduction from all sources to meet the drought target is estimated to be 42% for Monona, 49% for Waubesa, and 60% for Kegonsa.

Scenario for P load reductions

We developed a scenario that reduced the average P load by 50% from each lake’s direct drainage loading sources by utilizing all the P loading information and lake outlet pass-through factors generated in our study (Table 2). In the scenario, the load reduction was greatest in the Mendota watershed because that lake’s drainage source load represents nearly 70% of the direct drainage loads for all 4 lakes combined. In addition, this scenario demonstrated the cascading benefit to downstream lakes by reducing P loads to lakes farther upstream. For the 50% direct drainage load reduction scenario, Mendota’s pass-through load reduction to Monona is about equal to Monona’s direct drainage load reduction that would be achieved by management practices installed in that lake’s urban basin (excluding storm sewer basins draining directly to Lake Wingra due to its P load attenuation effect). For Waubesa, the pass-through load
importance of pass-through load reductions to Waubesa and Kegonsa relative to direct drainage load reductions, priority should be given to reducing Mendota’s P loading sources, followed by Monona’s P sources. The 50% average annual P load reduction goal for Mendota is still much higher than the estimated average surface water input load from Mendota’s watershed prior to European settlement in the early 1800s (Soranno et al. 1996).

Reducing outlet pass-through P loads relative to downstream direct drainage loads is also critical because P coming from a lake outlet is likely almost all “biologically available” for algal growth. Phosphorus originating from direct drainage sources is not all biologically available, however, because some of the P is strongly bound to sediments in runoff and not easily released in a biologically available form. Thus, even more priority should be given to reducing P sources in Mendota’s watershed for the pass-through benefits downstream.

Discussion

Long-term P loading data substantiated the occurrence of summer blue-green algal blooms in the 4 Yahara lakes after all wastewater inputs were diverted more than 50 years ago. Phosphorus loads to Lake Mendota, the headwater lake in the Yahara chain of lakes, were directly tied to agricultural and urban nonpoint pollution carried by runoff in streams and storm sewers from the lake’s large watershed. As a result, annual loads to Mendota since 1976 have been highly variable, ranging from relatively low P loads during drought years with little runoff to years with extreme runoff events that produced massive P loads. Large P loads also occurred in some years during January–March (Lathrop 2007) when the ground was frozen, thus allowing snowmelt and/or water from relatively light rains to run off from Mendota’s rural subwatersheds where raw manure had been extensively applied.

For Waubesa and Kegonsa, the pass-through reduction from Monona is 4 times Waubesa’s direct drainage load reduction. For Kegonsa, the pass-through reduction from Waubesa is about 2.5 times the direct drainage load reduction.

For Mendota and Monona, the total load reduction to each lake predicted in the scenario represents 92–93% of the target load reduction needed to achieve the late 1980s drought loading target for each lake. For Waubesa and Kegonsa, the reductions represent 85 and 68% of the respective target load reductions needed. Thus, to meet P loading reduction goals for the lower Yahara lakes, substantial P loading reductions are needed in the Mendota watershed; our recommendation is a reduction of 50% as a stated goal for the Yahara CLEAN Project. Given the

Fig. 11. Daily probability of Lake Monona having a surface water TP concentration <0.024 mg L⁻¹ (mesotrophy) during July–August relative to the long-term average P load condition and the presence or absence of the large-bodied *Daphnia pulicaria* grazer (see Fig. 9).

Fig. 12. Daily probability of Lake Monona having a Secchi disk transparency >2.0 m (mesotrophy) during July–August relative to the long-term average P load condition and the presence or absence of the large-bodied *Daphnia pulicaria* grazer (see Fig. 10).
to greater internal P loading due to the large area of epilimnetic waters in contact with bottom sediments.

Thus, lake depth and lake flushing rate dictated the high P input load passing through Waubesa and Kegonsa compared with Mendota (with Monona being intermediate). These relationships also confirmed that management practices to reduce P loads should be emphasized in Mendota’s watershed, with second priority given to Monona’s direct drainage basin. Improved water quality upstream cascades down the Yahara lake chain—a finding that has helped convince downstream lake users that money spent for management practices in Mendota’s watershed would benefit their lakes.

While the annual P loads to all 4 lakes were variable, in-lake TP concentrations during summer (Jul–Aug) corresponded consistently and relatively rapidly to the magnitude of those loads. When P loads were unusually high, summer TP was also high. In such summers, DRP was also elevated (especially in Waubesa and Kegonsa), a sign that algal growth was not P limited at that time. When annual loadings subsequently declined, however, lake TP also declined. Conversely, when P loads were low from prolonged droughts such as in 1987–1988, lake TP declined and even reached mesotrophic conditions (<0.024 mg L\(^{-1}\)) in Mendota.

This same drought caused low river flows and reduced TP in Mendota, diminishing loads to the lower 3 lakes in 1988–1989. Monona also achieved mesotrophy, but shallower Waubesa and Kegonsa did not, even though TP declined to its lowest level (~0.030 mg L\(^{-1}\)) since 1980 in the lower 2 lakes. This rapid response of all the Yahara lakes to changes in P loads is encouraging, indicating that immediate improvements can be expected in the lakes if management can successfully decrease P loads.

While the Yahara lakes’ water quality improves with drought-induced reductions of P loading, aggressive management is needed to sustain improvements in water quality. Long-term trends in water quality are not significant despite considerable effort to mitigate eutrophication (Lathrop 2007). Trends toward greater impervious surface in the watershed, higher densities of livestock, and more extreme rainfall and runoff events may partially offset the benefits of management actions to date. Thus, P load reductions of at least 50% in each of the 4 direct drainage basins are recommended to improve water quality, with most emphasis on the relatively large watershed of Lake Mendota; however, much deeper cuts to future P loads may be needed if trends in land use and runoff patterns continue.

Although lake TP concentrations were linked to P loads, and hence were a good indicator of a lake’s trophic state, Secchi disk readings sometimes produced different results, partly explained by the types of blue-green algal blooms that occur in the middle of the lake where limnological measurements were made. When TP concentrations were low, algal densities were also low and Secchi readings were relatively deep; both TP and Secchi TSIs signified mesotrophy. When TP levels were moderate to high, however, water clarity varied depending on the degree of *Daphnia* grazing on algae.

If large-bodied *Daphnia pulex* were absent, then smaller species of blue-green algae could dominate, reducing water clarity and causing the water to appear green throughout the whole lake. If *D. pulex* were present, then the smaller algae were removed by grazing, allowing larger filamentous and colonial blue-green algae to grow and dominate because they are not effectively controlled by grazing. Because many of these larger blue-green species have gas vacuoles that cause the algae to be buoyant, moderate winds can clear the middle of the lake as the algae are pushed to downwind shorelines where noxious floating scums can sometimes pile up. Our modeling results are consistent with this grazing effect.

Because Secchi readings are strongly affected by *Daphnia* grazing on algae, which in turn is mediated by food web dynamics controlled by fish and invertebrate predation, Secchi-TSIs can indicate mesotrophy when TP-TSIs values indicate eutrophy. The recent invasion by the spiny water flea (*Bythotrephes longimanus*, a predator on *Daphnia*) or the potential invasion by zebra mussels (*Dreissena polymorpha*, which enhance algal grazing) could strongly affect Secchi-TSIs. We therefore believe summer TP concentrations (or TP-TSI values) are a more useful indicator of lake water quality improvements due to P loading reductions. Secchi transparency readings (or Secchi-TSI values), which are more easily understood by lake users, can indicate food web dynamics in the lake, including changes that might occur from invasive species or fishery management.

The Yahara lakes, like many lakes in agricultural watersheds, are eutrophied by large nonpoint inflows of P. The response of the lakes to drought indicates that sharp, if temporary, reductions in P load cause notable improvements in water quality. Thus, P reduction has significant benefits despite the long history of excessive P inputs, a finding that offers some hope of mitigating eutrophication in these and other lakes subject to agricultural runoff. Our long-term data also indicate that management of fisheries and exclusion of invasive species are important determinants of water quality. Increased algal grazing by *Daphnia* can produce clearer water even during summer, although large colonial and filamentous blue-green algae that are not grazed may pile up as noxious floating scums on downwind shorelines if P loads are too high.

While the importance of P load reduction and intensive grazing are known from many lakes, the mitigation of eutrophication by a reduction of nonpoint pollution is...
difficult (Jeppesen and Sammalkorpi 2002, Sondergaard et al. 2007). Substantial and sustained commitments to nonpoint P load abatement are required to remedy eutrophication in the Yahara lakes, as with many other lakes around the world.

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References