Algal Blooms in the Baltimore, Maryland USA Reservoirs and Their Relationship to Water Quality Category

Report prepared for the City of Baltimore

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Abstract

An analysis approach used to characterize water quality conditions supportive of desirable phytoplankton populations was successfully applied to monitoring data for the three Baltimore (Maryland USA) drinking water reservoirs, Loch Raven, Prettyboy, and Liberty. Thresholds for evaluating nutrients and water clarity status were derived from the data and from published ranges for trophic classification of lakes and reservoirs. Total phosphorus classified as "better," or low enough to control algal growth, in 52.9% of all reservoir samples. Dissolved inorganic nitrogen never classified as "better," and 99.1% of the samples classified as "worst" (very enriched). Water clarity classified as "worst" or "poor" in 22.7% of all Secchi depth readings, which suggests algal populations are occasionally stressed by poor light conditions. Degraded water quality conditions–excess nitrogen *and* excess phosphorus *and* inadequate water clarity–have more variable chlorophyll *a* concentrations and a higher incidence of algal blooms. Least-degraded conditions with adequate/good water clarity and limiting phosphorus concentrations had few or no algal blooms. Chlorophyll as a surrogate for algal biomass accounted for an average 14.5%-17.4% of light attenuation in surface waters of the three reservoirs, and non-algal constituents such as inorganic sediment and particulate and dissolved organic matter accounted for an average 43.2% - 46.9% of light attenuation (excludes attenuation due to water itself). More than half of the total light attenuation can be caused by algae when chlorophyll *a* is greater than 30 $\mu g\ l^{-1}$. Total phosphorus (TP) concentrations less than 0.03 mg l^{-1} and Secchi depths greater than 5.5 m are protective against elevated chlorophyll a levels (i.e. >10 μg chl l^{-1}). If TP concentrations are somewhat above 0.03 mg l^{-1}, concurrent Secchi depths of 1.8-2.7 m^{-1} (unstratified) and 4.0-5.5 m^{-1} (stratified) are needed to avoid elevated chlorophyll *a* levels. When the water column is exceptionally clear, with very low levels of non-algal materials, elevated chlorophyll *a* levels are avoided if TP concentrations are below 0.01 mg l^{-1}. The unstratified period during winter and spring (usually November through April) had significantly poorer water quality conditions than the summer-fall stratification period (usually May through October). A link was observed between large magnitude changes in reservoir surface elevation and a higher frequency of algal blooms. Improving water clarity through sediment load reductions and minimizing rapid fluctuations in surface elevation could reduce the risk of algal blooms in Liberty and especially Prettyboy. Significant reductions in nitrogen loads will further minimize the risk of algal blooms.

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Introduction

High chlorophyll *a* concentrations occurred in the Loch Raven, Liberty, and Prettyboy reservoirs of Baltimore, Maryland, USA (Fig. 1) between January 1992 - July 2004, sometimes reaching concentrations >50 µg chl *a* l^{-1}. Elevated levels (ELs) of chlorophyll *a* were least frequent in Loch Raven and most frequent in Prettyboy. There were distinct spatial and temporal patterns common to all three reservoirs (Fig. 2). Chlorophyll *a* ELs occur throughout the water column during unstratified periods (usually November through March), when the reservoirs mix from surface to bottom. During the summer-fall stratification period, ELs occur either in the metalimnion layer (May, June, July) or the epilimnion layer (August, September, October). The metalimnion layer consists of those depths where the vertical temperature gradient changes most rapidly. It encompasses all thermocline(s), or changes of more than 1°C m^{-1}. The epilimnion is the wind mixed layer between the surface and the metalimnion.

The objective of this analysis was to characterize water quality conditions that encourage low chlorophyll *a* concentrations and the infrequent formation of ELs and algal blooms in the Loch Raven, Liberty, and Prettyboy reservoirs. Chlorophyll *a* ELs are defined in this analysis as instantaneous concentrations greater than 10 µg l^{-1}. The 10 µg l^{-1} threshold is lower than the Maryland Department of the Environment (MDE) interim action levels, which are a 30 µg chl *a* l^{-1} instantaneous measurement and a 10 µg chl *a* l^{-1} 30-day moving average (R Mandel, personal communication). The MDE interim action levels are representative of mesotrophic, or moderately nutrient enriched, lakes. These systems are characterized by mean chlorophyll *a* concentrations of about 3-11 µg l^{-1} and maximum concentrations of about 29 µg l^{-1}.

The approach used to analyze the Baltimore reservoirs is similar to one successfully applied to Chesapeake estuarine data for the same purpose (Buchanan et al. 2005). The estuarine study used independently determined, ecologically meaningful thresholds for dissolved inorganic nitrogen (DIN), ortho-phosphate (PO_4), and water column transparency (Secchi depth) to categorize water quality. Samples that met all the water quality thresholds were identified as reference and had low DIN and PO_4 concentrations and deep Secchi depths; those that met some but not all of the thresholds were identified as mixed; those that failed all three thresholds were identified as degraded and had high DIN and PO_4 concentrations and shallow Secchi depths. Phytoplankton communities in the reference samples had consistently low values of chlorophyll *a*, relatively stable proportions of the phytoplankton taxonomic groups, and low densities of key bloom-forming species. Phytoplankton communities in the degraded samples had frequent high (bloom) and low (bust) chlorophyll *a* levels, were more often dominated by harmful taxa, and were associated with lower dissolved oxygen levels. An important finding of the estuarine study was that as long as water column transparency is deep, nutrient concentrations do not have to be limiting before desirable features of the reference phytoplankton community–such as persistently low chlorophyll *a* concentrations–appear. The study delineated season- and salinity-specific nutrient and water clarity levels associated with a low risk of algal blooms.

Water quality thresholds and characteristics for similarly classifying and evaluating lake and reservoir conditions are available in the literature. Eutrophic lakes are turbid, nutrient enriched systems with frequent algal blooms and characteristic summer dissolved oxygen and pH profiles (e.g. Ryding and Rast 1989; Lampert and Sommer 1997, Fig. 8.11, Box 8.1; Wetzel 2001, Table 13-18, Figs. 9-2, 11-3). Oligotrophic lakes are nutrient limited systems, with desirable dissolved oxygen, chlorophyll *a*, and turbidity levels for drinking water and aquatic life. Mesotrophic lakes are in the middle of the continuum between eutrophic and oligotrophic.

Divisions between the trophic categories are not clear-cut because published ranges for nutrients and light often overlap. In addition, values of individual parameters can conflict as to how a lake should be classified, making rigid trophic classifications "subjective and fraught with exceptions" (Wetzel 2001). For example, Secchi depths in the Baltimore reservoirs can fall in the oligotrophic range while total phosphorus falls in the mesotrophic and eutrophic ranges. In this study, numeric thresholds to classify the Baltimore reservoir conditions were derived from the literature and from the data themselves. However, the classification ambiguities in the literature were avoided by creating water quality categories that group the data according to whether all, some, or none of three key water quality parameters meet specific, non-overlapping thresholds. Algal population features in each category were then examined.

Reservoir Descriptions

The three reservoirs are located in watersheds where approximately 59% of the land is used for agricultural, residential, urban, and transportation purposes (Table 1). Most of the forested and wetland areas border the reservoirs or their tributary streams (Fig. 1). Prettyboy is the smallest reservoir in terms of volume and surface area. It has a 130 ft. maximum depth (Table 1), a relatively steep depth-volume curve (Fig. 3a), and about a 1 year residence time. Of the three reservoirs, it experiences the greatest draw-downs (Fig. 3b). Loch Raven is downstream of Prettyboy. It has a slightly larger volume than Prettyboy, but ~60% more surface area and a much smaller (82 ft.) maximum depth, resulting in a shallower depth-volume curve (Table 1, Figs. 3a). Its watershed is approximately three times larger than Prettyboy's, resulting in about a 3 month residence time. Water supply withdrawals and releases from the upstream Prettyboy reservoir are made in such a way that Loch Raven experiences the smallest change in surface elevation (Fig. 3b). Liberty is the largest of the three reservoirs in terms of volume and surface area (Table 1); however, its volume-depth curve is relatively shallow and parallels that of Loch Raven (Fig. 3a). Liberty experiences significant draw-downs like Prettyboy (Fig. 3b). It has about a 1 year residence time. Conventional wisdom would suggest that the shallow maximum depth and depth-volume relationship in Loch Raven makes it more prone to algal blooms than Prettyboy and Liberty, but the reservoir has in fact the lowest frequency of blooms.

Ambient nitrogen and phosphorus concentrations are similar in the three reservoirs (Fig. 4). Average nitrate-nitrogen is slightly lower and ammonia-nitrogen slightly higher in Loch Raven. Average total phosophorus is lowest in Liberty. Water column transparencies are similar, except Loch Raven's summer Secchi depths are about 1 meter shallower (Fig. 5). Secchi depths are generally deepest in summer, between May and August, when the metalimnion is highest in the water column (Fig. 2). Seasonal water column transparency strongly tracks turbidity and water color and only weakly correlates with chlorophyll *a*, representing algal biomass. This suggests that reservoir light attenuation is primarily influenced by non-algal constituents – suspended sediments, dissolved organic matter, detritus and other non-algal materials. The mean chlorophyll *a* concentrations of 2-11 μg chl l^{-1} (Fig. 5), the maxima greater than 30 μg chl l^{-1}, the mean total phosphorus concentrations as high as 0.20 mg l^{-1} (Fig. 4), the mean dissolved inorganic nitrogen concentrations as high as 2.5 mg l^{-1} (Fig. 4), and the clinograde vertical profiles of dissolved oxygen (Fig. 6) and pH (Fig. 7) during many months indicate all three reservoirs are somewhere between mesotrophic and eutrophic status according to the lake classification criteria in Lampert and Sommer (1997) and Wetzel (2001).

Methods

Thresholds for classifying total phosphorus (TP), dissolved inorganic nitrogen (DIN), and water clarity, or water column transparency, as “worst,” “poor,” “fair” (water clarity only), “better,” or “best” were derived from multiple sources. Phosphorus and water clarity classes (Fig. 8) are based on published TP and Secchi depth ranges for lakes and reservoirs of different trophic status (Ryding and Rast 1989, Table 4.2; Lampert and Sommer 1997, pg 310-314; Wetzel 2001, Table 13-18; U. S. Environmental Protection Agency 2003, Table V-8). A “fair” category was included for Secchi depth because of the strong overlap in the eutrophic and mesotrophic ranges (Fig. 8). Nitrogen is represented by the summed concentrations of nitrate (NO_3) and ammonia (NH_4), but includes nitrite (NO_2) when that parameter was measured (Liberty, January 1992 - June 1997). Published ranges are available for total nitrogen (TN), a parameter that was not measured in the reservoir studies. The thresholds for delineating DIN classes were therefore derived from the Fisher and Gustafson (2003) bioassay results for natural Chesapeake populations. The bioassays showed that samples with >0.07 mg DIN l^{-1} did not increase primary production when nitrogen was added while samples with <0.07 mg DIN l^{-1} did. Therefore, 0.07 mg DIN l^{-1} represents a population growth-limitation threshold. Slightly lower thresholds (<0.05-0.06 mg DIN l^{-1}) have been determined for microbial growth in unpolluted rivers (Wetzel 2003, Table 12-17). A nitrogen threshold to delineate the “poor” and “worst” classes was chosen to accommodate the relatively high detection limits of one of the reservoir study’s nitrate methods (Fig. 8). The classification thresholds for Secchi, TP, and DIN are provided in Table 2.

For each station-date event, nutrient data from each sampling depth and the surface Secchi depth measurement are individually classified. The station’s Secchi depth classification is then associated with the nutrient samples collected below the surface. Water quality category designation is assigned to each sample’s results according to the rules in Table 2. Results from the hypolimnion, or bottom layer during stratification periods, were not considered. In most lakes, algal cells in the hypolimnion are prevented by thermoclines from circulating into upper layers where light is adequate for photosynthesis. Therefore, hypolimnetic cells are usually assumed to be inactive or senescent. Results from the metalimnion are considered to represent viable phytoplankton populations because the compensation depth (1% surface irradiance), or bottom of the photic zone, was frequently in the metalimnion.

The extinction coefficient for chlorophyll *a* (η_{CHL}) was determined from the data in order to estimate the proportion of light attenuation due to suspended algae, or phytoplankton ($\%\eta_{CHL}$). Total light attenuation, represented by the net extinction coefficient η_{TOT}, was calculated from Secchi depth (Z, in meters) with the equation $\eta = 1.11\ Z^{-0.73}$ (from Coles and Wells 2003). The Loch Raven-Prettyboy data were binned into a matrix of homogeneous groups according to apparent color, turbidity, and chlorophyll a. Only data from the mixed surface layer (epilimnion) were used, since Secchi depth is determined in the first few meters of the water column. The increase in η with increasing chlorophyll *a* was then determined for the color-turbidity-chlorophyll groups with sufficient data points. (Liberty data were not used because color was measured differently and there were insufficient data to do an independent determination of η_{CHL}.) The average value of η_{CHL} ($m^{-1}\ \mu g\ chl^{-1}\ l^{-1}$) was multiplied by chlorophyll *a* concentration and divided by η_{TOT} to compute the proportion of total light attenuation due to chlorophyll *a* ($\%\eta_{CHL}$) for each record. The extinction coefficient of the non-algal constituents was determined with the equation $\eta_{OTHER} = \eta_{TOT} - \eta_{CHL} - \eta_{H2O}$, where $\eta_{H2O} = 0.19$ (from measurements made in oligotrophic lakes, sources listed in Cole and Wells 2003).

Results

True reference conditions (Better category) were not present in the 1992 - 2004 reservoir samples (Table 3). The Mixed Better Light category represents the least-degraded conditions in the reservoirs. This category was present during early summer stratification (May - August) but uncommon or absent during the remainder of the year. Degraded conditions, or the Poor and Mixed Poor Light categories, were most prevalent between December and April when the water column was not stratified. They were uncommon or absent during early summer stratification. The Mixed Fair Light category, with marginal Secchi transparency depths and excess nitrogen and/or phosphorus concentrations, was the predominant category throughout most of the year in all three reservoirs (Fig. 9).

The threshold for the "better" DIN class (<0.07 mg l^{-1}) was never met in the three reservoirs, which precluded finding reference, or Better category, conditions. Approximately 55%, 98%, and 80% of samples in the Mixed Better Light category in Loch Raven, Liberty, and Prettyboy, respectively, met the thresholds for "better" phosphorus *and* "better" Secchi but failed to place in the Better category because of the high DIN concentrations. Samples in the Mixed Fair Light category failed to place in the Mixed Better Light category because Secchi depths were between 2.2 and 5.5 meters. In these Mixed Fair Light samples, the threshold for the "better" phosphorus class was met in 73%, 98%, and 80% of the time for Loch Raven, Liberty, and Prettyboy, respectively, which is similar to percentages in the Mixed Better Light category.

Chlorophyll *a* concentrations in the least-degraded, Mixed Better Light category were almost always <10 µg chl *a* l^{-1} in Prettyboy and Liberty, regardless of stratification and layer (Figs. 10, 11A). Chlorophyll *a* ELs occurred in 7 of the 43 metalimnion Mixed Better Light samples in Loch Raven (15.2%) but did not exceed 14 µg chl *a* l^{-1}.

The prevalent Mixed Fair Light category appears to represent an intermediate state between the Poor and Mixed Better Light categories. The frequency of chlorophyll *a* ELs ranged from 1.6% - 21.1% (Figs. 10, 11A), and chlorophyll *a* rarely exceeds 30 µg l^{-1}.

Chlorophyll *a* concentrations in the Poor and Mixed Poor Light water quality categories were generally the highest and most variable (Fig. 10). Chlorophyll *a* ELs occurred in 13% - 39% of samples from unstratified waters, in 22% - 67% of samples from stratified epilimnion waters, and in 6% - 50% of samples from stratified metalimnion waters (Fig. 11A). Approximately 3.3% of all Poor and Mixed Poor Light samples were >30 µg l^{-1}. Chlorophyll distributions in samples from Mixed Poor Light, when this category was present, are very similar to those in the Poor category.

"Poor" and "worst" light classes occur frequently enough in the reservoirs to indicate that light is sometimes inadequate, especially during the unstratified period (Table 3). They occurred in 25.4% of Loch Raven station-date sampling events, 18.3% of Liberty events, and 35.7% of Prettyboy events. When Secchi depth classified as "poor" or "worst" during periods of stratification, the compensation depth or bottom of the photic zone (1% surface light level) occurred within the epilimnion and not below it. At these times, light levels would theoretically be inadequate for photosynthesis in the epilimnion. "Poor" and "worst" light classes were coincidental with >30 µg chl l^{-1} algal blooms less than 5% of the time, and with ELs 10-30 µg l^{-1} less than 35% of the time, which indicates that turbidity caused by algal blooms is not primarily responsible for the poor water column transparency in the reservoirs.

Computed extinction coefficients for algal and non-algal constituents in the water column confirm that light attenuation in the reservoirs is caused primarily by non-algal constituents most of the time. However, more than half of total light attenuation is caused by algae when chlorophyll *a* is greater than 30 μg l^{-1}. The monthly-weighted average %light attenuation due to non-algal constituents (excludes water itself) is 46.9% in Loch Raven, 43.2% in Liberty, and 46.0% in Prettyboy. Average %light attenuation due to chlorophyll *a* is 14.1% in Loch Raven, 14.2% in Liberty, and 16.7% in Prettyboy (Fig. 12). Average light attenuation due to non-algal constituents is highest during the unstratified period from late autumn to early spring (November to March). This coincides with the period of highest average surface flows into the reservoirs, which suggests that the source of the heightened non-algal constituents is from runoff. Average light attenuation due to chlorophyll *a* is highest in the unstratified period from February to March, and the stratification period from August to October. Individual estimates of %light attenuation due to chlorophyll *a* that were greater than 50% tended to occur in spring and summer in Loch Raven' epilimnion and in spring and fall in Liberty and Prettyboy's epilimnions.

Discussion

The three Baltimore reservoirs are enriched with nutrients, especially nitrogen. Over the course of almost 12 years (January 1992 - July 2004), samples representing the Better, or reference, category were never experienced due to the reservoirs' very high nitrogen levels, but all other water quality categories were adequately represented (Table 2). The reservoirs experienced a sufficiently broad range of water quality conditions to allow an analysis of some factors controlling algal blooms, and an empirical determination of the chlorophyll light extinction coefficient, η_{CHL} (m^{-1} μg chl^{-1} l^{-1}) .

WATER QUALITY CATEGORIES AND BLOOM FREQUENCY

Elevated levels (Els) of chlorophyll *a*, defined in this analysis as concentrations greater than 10 μg l^{-1}, occurred infrequently in the reservoir Mixed Better Light category. Water quality conditions in this category always met the threshold for the "better" water clarity class (Secchi depth >5.5m) and often met the threshold for the "better" phosphorus class (TP <0.03 mg l^{-1}). They always failed the threshold for the "better" nitrogen class (DIN <0.07 mg l^{-1}). Chlorophyll *a* ELs were almost as infrequent in the reservoir Mixed Fair Light category, which differs from the Mixed Better Light category in its water clarity range (>2.2 - 5.5 m Secchi depth) but has similar nutrient characteristics. Overall, ELs occur in just 3.1% of the Mixed Better Light samples (n=354) and in 8.4% of the Mixed Fair Light samples (n=2,765). The Mixed Better Light category occurs primarily from May to August while the Mixed Fair Light category occurs throughout the year (Fig. 9). The Mixed Better Light category represents the least degraded conditions presently experienced in the three reservoirs, followed by the Mixed Fair Light category.

Chlorophyll *a* ELs were more frequent in the reservoir Mixed Poor Light category. Water quality conditions in this category always failed the thresholds for the "better" and "fair" water clarity classes and the threshold for the "better" nitrogen class, but always met the threshold for the "better" phosphorus class. In other words, phosphorus concentrations were limiting for algal growth (desirable) but light was inadequate and nitrogen excessive (undesirable). Algal blooms were found in 19.7% of all Mixed Poor Light samples (n=178). The reservoir Mixed Poor Light category occurs primarily on sampling dates between October and April when the water column was unstratified.

Chlorophyll *a* ELs were most frequent in the Poor category, where water quality conditions failed all the nitrogen, phosphorus, and water clarity thresholds for the "better" (and "fair" Secchi) classes. Both nitrogen and phosphorus concentrations are excessive and light is inadequate. The Poor category occurs primarily between November and April when the water column was unstratified. Overall, algal blooms were present in 29.7% of all Poor category samples (n=637).

ABBREVIATED WATER QUALITY CATEGORIES

The infrequent occurrence of chlorophyll *a* ELs in the Mixed Better Light and Mixed Fair Light categories makes the case that nitrogen may not be an important water quality factor with regard to algal bloom management in the Baltimore reservoirs. DIN in these categories always exceeds the water quality classification threshold of 0.07 mg l^{-1} while TP may or may not exceed its threshold of 0.03 mg l^{-1} and Secchi depth always meets its better (>5.5 m) or fair (>2.2 - 5 m) thresholds. The literature generally points to phosphorus as the critically important, or limiting, nutrient controlling phytoplankton population growth in freshwater systems. Mixed Better Light and Mixed Fair Light data records with excess TP in fact tend to have substantially higher frequencies of ELs than those with limited TP, reiterating the importance of phosphorus in algal growth and bloom formation in freshwater systems (Table 4).

The Baltimore reservoir data were re-categorized with only the Secchi and TP classification criteria in Table 2 in order to determine if the original DIN classification criteria unnecessarily biased the analyses. The abbreviated water quality categories were Better (both Secchi and TP are better/best), Mixed Better Light (Secchi is better/best, TP is poor/worst), Mixed Fair Light (Secchi is fair, TP is any class), Mixed Poor Light (Secchi is poor/worst, TP is better/best), and Poor (Secchi is poor/worst, TP is poor/worst). The re-categorization divided data records from the original Mixed Better Light category into a new Mixed Better Light category and a Better category. It did not change the analysis results (Fig. 11B). Including the DIN classification thresholds in the original water quality scoring simply made the least degraded water quality category Mixed Better Light rather than Better.

WATER CLARITY

The analysis results indicate that the importance of water column transparency, or clarity, as a factor controlling algal population densities may be greater than the importance of algae as a material that absorbs/scatters light energy and reduces water clarity. This differs from the conventional view that chlorophyll *a* is a primary cause of poor water clarity, and not a consequence of it. Significant relationships ($p<0.01$) occur between chlorophyll *a* and Secchi depth in the reservoir data (Loch Raven $r^2 = 0.05$, Liberty $r^2 = 0.36$, Prettyboy $r^2 = 0.29$), which tends to support "chlorophyll as cause" point of view and make the "chlorophyll as consequence" argument (i.e., poor water clarity enhances algal bloom frequency) appear circular.

Closer examination of the chlorophyll-Secchi plots shows that instances of water clarity in the poor light class have both high (>10 μg l^{-1}) and low (<1 μg l^{-1}) chlorophyll *a* values. The high chlorophyll *a* values could reasonably be the cause of some of the low Secchi depth values, but factors other than algae are causing low Secchi depths when chlorophyll *a* values are moderate or low. Turbidity-Secchi plots show that turbidity values are always high at low Secchi depths and low at high Secchi depths, and the correlation coefficients are higher (Loch Raven $r^2 = 0.52$, Liberty $r^2 = 0.50$, Prettyboy $r^2 = 0.53$). Turbidity is a reduction in water clarity due to absorption and scattering of light by suspended particles, which includes inorganic sediments and/or suspensoids (e.g., colloidal and particulate calcium carbonate) and algae. The apparent color-Secchi plots show that color values are always high at low Secchi depths and low at high Secchi depths, and apparent color–like turbidity–correlates more closely with water clarity than chlorophyll *a* (Loch Raven $r^2 = 0.45$, Prettyboy $r^2 = 0.45$). Apparent color is related to the concentration of dissolved organic acids such as tannins and lignins, which can give the water a tea color. Since the samples are unfiltered, the color measurements also include the effect of the chlorophyll *a* green color. Although both the turbidity and apparent color measurements do not exclude the effects of algal matter, the stronger, tighter relationships between Secchi depth and turbidity and apparent color suggest that algal biomass (chlorophyll *a*) is not a major cause of light attenuation most of the time. This is particularly true for Loch Raven and Prettyboy reservoirs which have essentially flat Secchi-chlorophyll relationships for Secchi depth less than 5 m.

Extinction coefficient estimates for algal (η_{CHL}) and non-algal (η_{OTHER}) constituents further support the hypothesis that non-algal constituents usually cause the majority of light attenuation in the three reservoirs. Fig. 13 shows the minimum, average, and maximum values of $\%\eta_{CHL}$ and $\%\eta_{OTHER}$ across the spectrum of Secchi depths experienced in the reservoirs. The non-algal constituent includes suspended inorganic sediments, suspended organic particles excluding algae (e.g. detritus, zooplankton), and dissolved organic and inorganic compounds, but does not include water itself. Depending on the reservoir, $\%\eta_{CHL}$ remains unchanged or increases slightly while $\%\eta_{OTHER}$ increases as Secchi depth decreases. The mean $\%\eta_{CHL}$ is less than 40% at all but two Secchi depths intervals, and the 10-period rolling average is always less than 25%.

Water clarity likely controls algal bloom frequency through its effect on chlorophyll cell content. Persistent low light environments are known to cause physiological changes in algal cells that make them increase their chlorophyll cell content (Chl *a*:C) significantly. This response allows them to maintain sufficient photosynthesis to survive (Kirk 1994). Buchanan et al. (2005) observed higher median values of the Chl *a*:C ratios and a broader range of Chl *a*:C values in natural, low light algal populations. They speculate that the higher Chl *a*:C ratios allow these cells to photosynthesize more rapidly when poor light conditions suddenly improve. Upwelling and weather-related circulation patterns can periodically set up favorable light microhabitat in what are usually poor, or low light, environments. In nutrient rich environments, these circumstances result in the rapid formation of algal blooms. Algal populations in low light environments therefore show a wide range of Chl *a*:C ratios and biomass concentrations (blooms and busts) depending on whether population growth is suppressed by light-limitation or happens to be responding to a favorable light microhabitat.

FLUCTUATIONS IN SURFACE ELEVATIONS

Minimizing rapid rises or falls in reservoir surface elevations may further reduce the risk of algal blooms in the Liberty and Prettyboy, where fluctuations are most severe (Fig. 3b). Loch Raven's flatter depth-volume profile and shallower depths (Table 1, Fig. 3a) suggest it should be more susceptible to algal blooms than Prettyboy–which is chemically similar to Loch Raven but deeper and with a steeper depth-volume profile–or Liberty. The opposite is found (Fig. 2). Examination of the time-series data shows that of the major algal bloom events (>30 μg chl *a* l^{-1}), four of the nine Prettyboy events and four of the eleven Liberty events occurred after prolonged drawdowns (<-0.1 ft day^{-1}, <-0.033 m day^{-1}) or periods of rapid increase in reservoir surface elevation (>0.1 ft day^{-1}, >-0.033 m day^{-1}). Loch Raven experienced seven major algal blooms - none of them was associated with rapid fluctuations in surface elevation.

PROTECTIVE WATER QUALITY CONDITIONS

Water column transparency, or water clarity, appears to be a significant factor controlling the frequency of algal blooms in the three Baltimore reservoirs, despite the reservoirs' fairly good water clarity. Non-algal constituents affect water clarity more than the algal constituent most of the time, therefore management of water clarity will be best implemented through sediment and organic matter load reductions. Reservoir waters with Secchi depths greater than about 5.5 m (18 ft) have very few chlorophyll *a* ELs, or >10 μg chl l^{-1}, regardless of nutrient concentrations. Below this Secchi threshold, which was derived from literature values for low mesotrophic lakes and reservoirs, the frequency of chlorophyll *a* ELs rises.

The important influence of light should not minimize the equally important influence of nutrients, and in particular phosphorus, on ELs and algal bloom formation. Fig. 14 shows that although minimal (5^{th}%) and median values of chlorophyll *a* remain low across a gradient of TP concentrations, maximal (95^{th}%) values are higher at elevated TP concentrations, indicating more frequent algal blooms. The excess-TP versus limited-TP comparisons in Table 4 reiterate the influence of TP in bloom formation.

The computed η_{OTHER} values, or extinction coefficients of non-algal matter in the water column, and the TP classifications allow us to further explore and refine our understanding of conditions that are protective against ELs and algal blooms. Plots of the frequency of chlorophyll *a* ELs versus computed η_{OTHER} for the four TP classes at surface (0-10 ft), middle (20-30 ft) and deep (40-50 ft) depths in the reservoirs show several distinct response patterns (Fig. 15). First, EL frequencies in the worst and poor TP classes are typically higher than those in the better and best TP classes, regardless of η_{OTHER}. TP concentrations below 0.03 mg l^{-1} (better/best TP classes) are generally protective against ELs. Second, EL frequency tends to increase in surface waters as η_{OTHER} values increase. This supports the "chlorophyll as consequence" of poor water clarity point of view. The pattern disappears and EL frequencies are consistently low when TP concentrations are below 0.03 mg l^{-1} (better/best TP classes). Third, EL frequencies can be high when η_{OTHER} values are very low (i.e., <0.2 m^{-1}), except if TP <0.01 mg l^{-1} (best TP classes). This indicates that very low TP levels are necessary to avoid ELs and algal blooms when concentrations of non-algal constituents in the water column are low and water clarity is exceptionally good.

Water quality conditions that protect against ELs and algal blooms could be largely accomplished if TP concentrations are kept below 0.03 mg l^{-1} in the three reservoirs or Secchi depths are greater than 5.5 m. These conditions are found in the Mixed Better Light category with limiting TP (Table 4). ELs could be expected to occur in about 2.9% of the samples. If TP concentrations are above 0.03 mg l^{-1}, η_{OTHER} values of 0.3-0.5 m^{-1} (unstratified) and 0.1-0.2 m^{-1} (stratified) may confer some protection against ELs. These η_{OTHER} values roughly equate to Secchi depths of 1.8-2.7 m^{-1} (unstratified) and 4.0-5.5 m^{-1} (stratified) if chlorophyll *a* concentrations are minimal. They overlap Secchi values in the "fair" class, i.e. 2.2 - 5.5 m (Table 2). TP concentrations below 0.01 mg l^{-1} would be needed to protect against ELs during periods of exceptional water clarity, when η_{OTHER} values are very low (i.e., <0.1 m^{-1}). Very low η_{OTHER} values roughly equate to Secchi depths >5.8 m^{-1} if chlorophyll *a* concentrations are minimal.

Mixed Better Light conditions with limiting TP occur the least often in the unstratified period during winter and spring. Sediment, organic carbon, and phosphorus loading reductions during winter and spring are likely to bring about the sharpest drop in the frequency of ELs and algal blooms during that period.

The reservoirs' response to low nitrogen levels could not be determined empirically from the data because there were no instances when DIN met the "better" class threshold. Lake systems are known to be more sensitive to phosphorus loading that to nitrogen loading; however, mesotrophic systems with reliably low concentrations of chlorophyll *a* typically have TN concentrations less than 1.6 mg l^{-1} (Wetzel 2003, Table 13-18). Concentrations of DIN–the inorganic component of TN–are significantly higher than this TN threshold in the Mixed Better Light category of the reservoirs, reaching as high as high as 3.1 mg l^{-1}. The advantage of reducing nitrogen loadings to the reservoirs is that low nitrogen concentrations offer another means of reducing algal bloom frequency and limiting the magnitude of the blooms when they do occur.

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Table 1. Baltimore reservoir and watershed statistics. Data sources: Baltimore Bureau of Water and Wastewater, http://www.baltimorecity.gov/government/dpw/wwwfacts.html; Regional Earth Science Applications Center (RESAC) Chesapeake Bay Watershed Land Cover - 2000 - Version 1.05 GIS coverage, http://www.geog.umd.edu/resac/outgoing.

Loch Raven	Liberty	Prettyboy
Reservoir * Elevation above mean sea level 240 feet * Total length of dam 650 feet * Height of crest above stream bed 82 feet * Length of shore line at crest elevation 50 mi * Flooded area at crest elevation 2,400 acres * Initial storage capacity: 23 billion gallons * Built 1912 – 1914 (elevation 188 feet) * Crest raised 52 feet: 1921 – 1922 (elevation 240 feet) * Intakes lead to Montebello Pumping Station below dam Watershed * Area of watershed: 233 square miles * Major inflow: Gunpowder River * Land uses: 34.8% - agriculture, pasture, grasses 40.8% - forest, wetlands 23.2% - residential, urban, transportation, extractive, barren	Reservoir * Elevation above mean sea level 420 feet * Total length of dam 704 feet * Height of crest above stream bed 160 feet * Length of shore line at crest elevation 82 mi * Flooded area at crest elevation 3,100 acres * Initial storage capacity: 43 billion gallons * Built: 1951 – 1954 * Intakes lead to Ashburton Filtration Plant Watershed * Area of watershed: 164 square miles * Major inflow: N. Branch Patapsco River * Land uses: 34.3% - agriculture, pasture, grasses 36.3% - forest, wetlands 27.6% - residential, urban, transportation, extractive, barren	Reservoir * Elevation above mean sea level 520 feet * Total length of dam 845 feet * Height of crest above stream bed 130 feet * Length of shore line at crest elevation 46 mi * Flooded area at crest elevation 1,500 acres * Initial storage capacity: 20 billion gallons * Construction completed: 1933 * Water releases are made to maintain water level in Loch Raven located downstream Watershed * Area of watershed: 80 square miles * Major inflow: Gunpowder Falls * Land uses: 40.8% - agriculture, pasture, grasses 42.7% - forest, wetlands 14.6% - residential, urban, transportation, extractive, barren

Table 2. Classification thresholds and water quality categories used to characterize phytoplankton conditions in Baltimore reservoirs. Worst is a subset of the data in Poor; Best is a subset of the data in Better.

Water Quality Category:	(Worst)	Poor	Mixed Poor Light	Mixed Fair Light	Mixed Better Light	Better	(Best)
Secchi (meters)							
thresholds:	<1.0	≤ 2.2	≤ 2.2	>2.2 - 5.5	>5.5	>5.5	>9.4
class(es):	worst	poor or worst	poor or worst	fair	better or best	better or best	best
DIN (mg l^{-1})							
thresholds:	>0.70	≥0.07	DIN or TP or both are in better or best class	all values of DIN and TP	DIN or TP or both are in poor or worst class	<0.07	<0.03
class(es):	worst	poor or worst				better or best	best
TP (mg l^{-1})							
thresholds:	>0.10	≥0.03				<0.03	≤0.01
class(es):	worst	poor or worst				better or best	best

Table 3. Monthly frequencies of the water quality categories in Loch Raven, Liberty, and Prettyboy Reservoirs, for all samples regardless of depth and stratification layer. Light classification is based on each sampling events Secchi depth, while nutrient classification is based on individual samples. The sum of all adequate-light categories (i.e., Better, Mixed Better Light, Mixed Fair Light) is shown in far right column. Average percent of adequate-light categories is indicated for typically stratified (May-Oct) and non-stratified (Nov-Apr) periods.

Month	Better	Mixed Better Light	Mixed Fair Light	Mixed Poor Light	Poor	% Adequate-Light Monthly Mean ± CI
LOCH RAVEN						
1	-	-	56.3%	22.3%	21.4%	56.3%
2	-	-	55.3%	3.5%	41.2%	55.3%
3	-	-	36.5%	11.8%	51.7%	36.5%
4	-	-	46.3%	17.7%	36.1%	46.3%
5	-	-	90.7%	-	9.3%	90.7%
6	-	11.5%	84.2%	-	4.3%	95.7%
7	-	24.8%	75.2%	-	-	100.0%
8	-	10.0%	86.3%	-	3.8%	96.3%
9	-	-	98.4%	-	1.6%	98.4%
10	-	4.3%	90.6%	2.9%	2.2%	94.9%
11	-	-	78.6%	13.6%	7.8%	78.6%
12	-	-	57.9%	13.1%	29.0%	57.9%
			Stratified (May-Oct)			96.0% ± 2.6%
			Non-Stratified (Nov-Apr)			56.9% ± 13.1%
LIBERTY						
1	-	-	77.3%	3.4%	19.3%	77.3%
2	-	4.3%	66.0%	9.6%	20.2%	70.2%
3	-	3.6%	43.8%	19.6%	33.0%	47.3%
4	-	6.5%	67.3%	16.1%	10.1%	73.7%
5	-	21.4%	76.7%	1.9%	-	98.1%
6	-	36.2%	61.6%	2.3%	-	97.7%
7	-	46.1%	50.7%	3.2%	-	96.8%
8	-	8.6%	86.2%	2.9%	2.4%	94.8%
9	-	4.6%	74.1%	14.2%	7.1%	78.7%
10	-	-	73.0%	23.0%	4.0%	73.0%
11	-	-	84.3%	11.9%	3.8%	84.3%
12	-	-	72.5%	16.3%	11.3%	72.5%
			Stratified (May-Oct)			89.8% ± 13.2%
			Non-Stratified (Nov-Apr)			70.9% ± 11.6%
PRETTYBOY						
1	-	-	16.9%	33.9%	49.2%	16.9%
2	-	-	19.5%	18.2%	62.3%	19.5%
3	-	-	26.5%	16.8%	56.6%	26.5%
4	-	-	41.3%	9.3%	49.3%	41.3%
5	-	-	100.0%	-	-	100.0%
6	-	26.5%	73.5%	-	-	100.0%
7	-	41.8%	58.2%	-	-	100.0%
8	-	9.6%	77.1%	3.6%	9.6%	86.7%
9	-	-	70.4%	-	29.6%	70.4%
10	-	-	83.5%	9.4%	7.1%	83.5%
11	-	-	64.9%	1.1%	34.0%	64.9%
12	-	-	36.4%	18.2%	45.5%	36.4%
			Stratified (May-Oct)			90.1% ± 9.7%
			Non-Stratified (Nov-Apr)			32.8% ± 17.0%

Table 4. Comparison of Mixed Better Light and Mixed Fair Light samples with excess TP (poor/worst classes) and with limited TP (better/best classes). DIN concentrations are excess (poor/worst classes) in all records. "nd" = insufficient data. Mixed Better Light and Mixed Fair Light samples with excess TP tended to have higher algal bloom frequencies than those with limited TP.

	Loch Raven	Liberty	Prettyboy	Overall	
Mixed Better Light Category					
Excess TP (poor/worst classes)					
n	42	3	14		
freq ELs (%)	11.9%	nd	nd	11.9%	estimate
avg chl (ug l^{-1})	5.2	1.4	3.3		
avg TP (mg l^{-1})	0.070	0.070	0.072		
Limited TP (better/best classes)					
n	52	189	54		
freq ELs (%)	5.8%	1.1%	1.9%	2.9%	
avg chl (ug l^{-1})	4.1	1.8	2.9		
avg TP (mg l^{-1})	0.016	0.010	0.011		
Mixed Fair Light Category					
Excess TP (poor/worst classes)					
n	657	82	249		
freq ELs (%)	6.5%	28.0%	17.3%	17.3%	
avg chl (ug l^{-1})	4.6	7.7	6.4		
avg TP (mg l^{-1})	0.089	0.069	0.108		
Limited TP (better/best classes)					
n	502	978	246		
freq ELs (%)	5.6%	7.6%	7.3%	6.8%	
avg chl (ug l^{-1})	4.9	4.6	5.3		
avg TP (mg l^{-1})	0.018	0.015	0.015		

Figure 1. Watershed land uses of the Baltimore drinking water reservoirs, Maryland, USA. Data source: Regional Earth Science Applications Center (RESAC) Chesapeake Bay Watershed Land Cover - 2000 - Version 1.05 GIS coverage, http://www.geog.umd.edu/resac/outgoing.

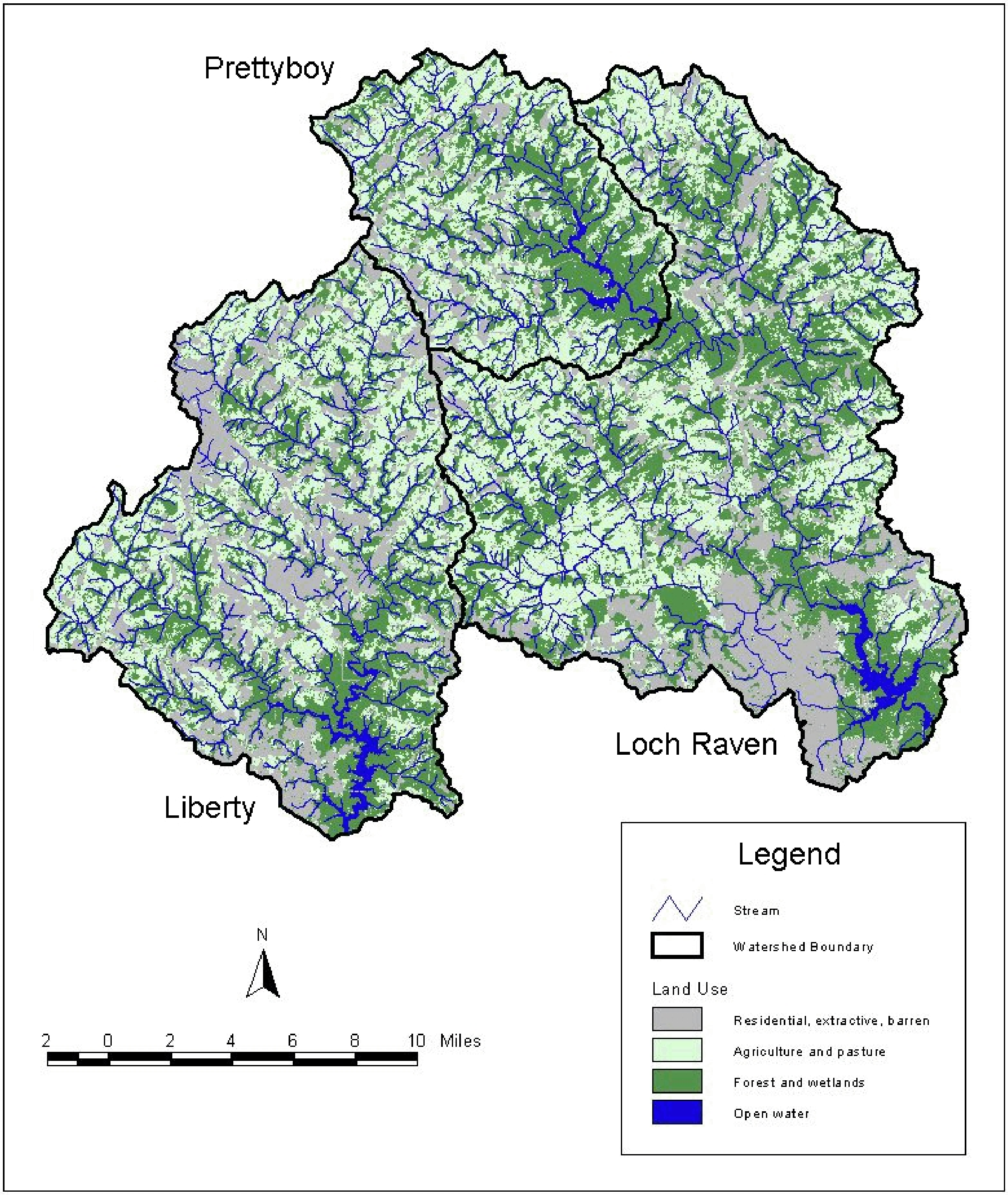


Figure 2. Spatial and temporal patterns of chlorophyll *a* elevated levels (i.e., > 10 µg chl l^{-1}) in Loch Raven, Liberty, and Prettyboy reservoirs for January 1992 - July 2004. Size of bubble reflects frequency of ELs; largest bubble is 54% (Prettyboy, April, ~3m). Horizontal line indicates average depth of top of metalimnion during periods of stratification. Solid upside-down lollipop indicates average measured Secchi depth (Z_s), or approximately 10% of surface light. Open upside-down lollipop indicates the Secchi-based computation of compensation depth, or approximately 1% of surface light (i.e., $4.60517/(1.11Z_s^{-0.73})$). Compensation depths are shown only for September - April. The water column is unstratified in these months or the metalimnion is very deep, so waters above the computed compensation depth are assumed to be well mixed and Secchi-based calculations would be appropriate to use. Compensation depths computed from Secchi depths for May - August are not shown. Light attenuation in the high algal concentrations present in the metalimnion would differ significantly from light attenuation in surface waters, and Secchi-based calculations would overestimate compensation depth. Depths above the compensation depth are generally considered to be in the euphotic zone of the water column.

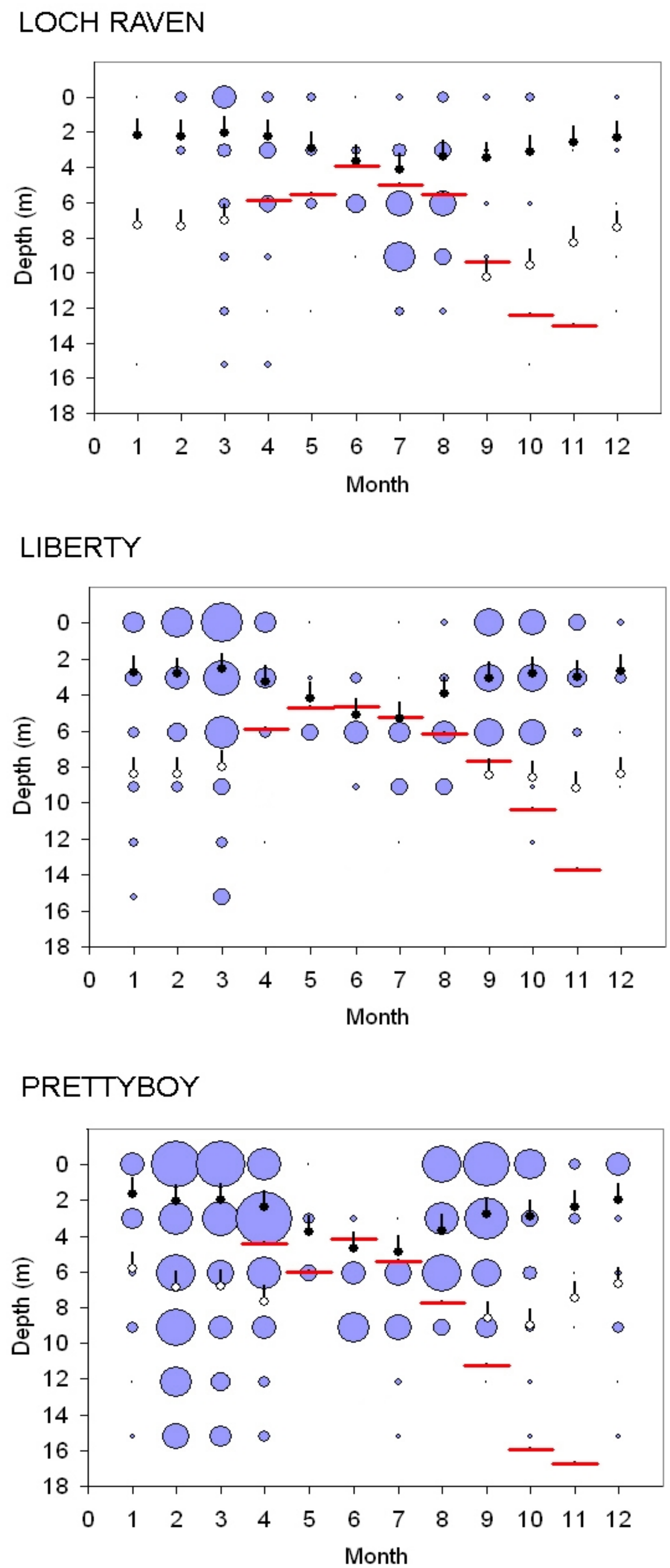


Figure 3a. Reservoir capacity versus surface elevation.

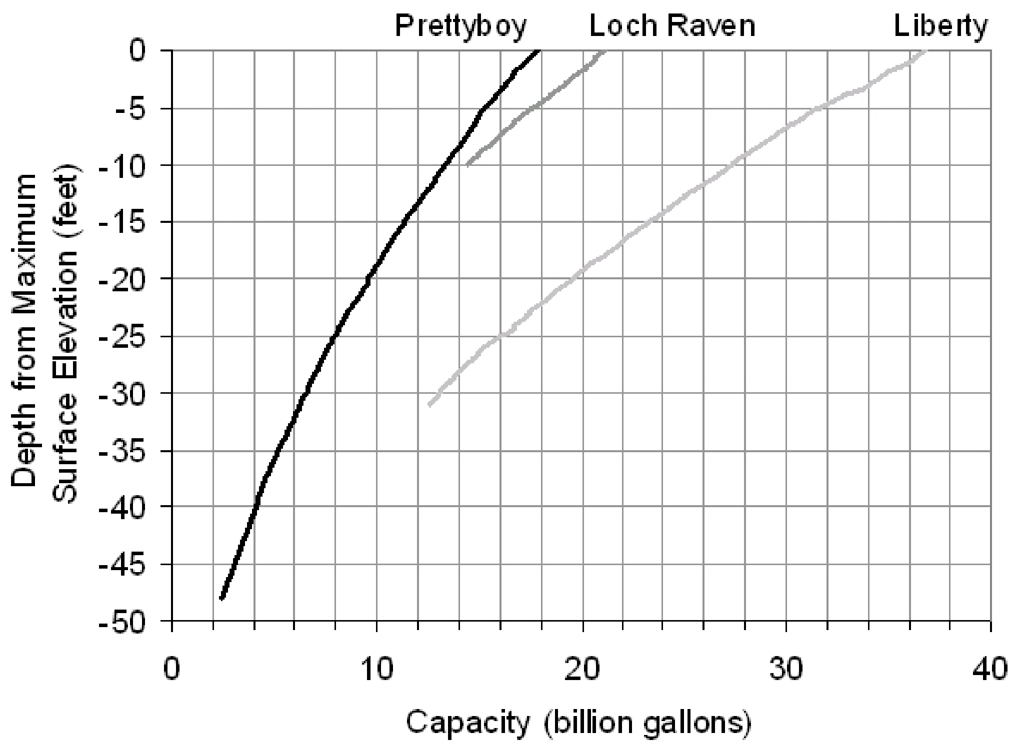


Figure 3b. Changes in reservoir surface elevation, January 1992 - July 2004. Elevations were first normalized to the highest value experienced in the period of record.

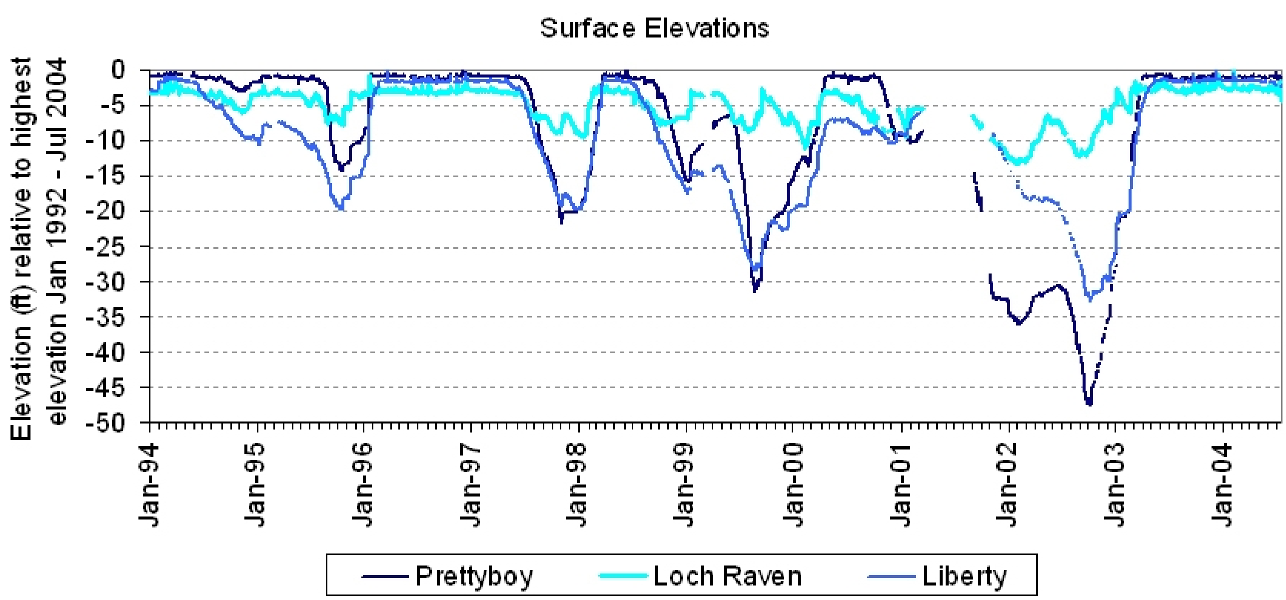


Figure 4. Average monthly concentrations of nitrate-nitrogen, ammonia-nitrogen, and total phosphorus. During the non-stratification period (usually November - March), the reservoirs mix from surface to bottom and the entire water column is considered the epilimnion. During the stratification period (usually April - October), the epilimnion is the mixed layer between the water surface and the top of the metalimnion. The metalimnion encompasses all the depths where thermoclines become established. The hypolimnion lies below the metalimnion, to the reservoir bottom.

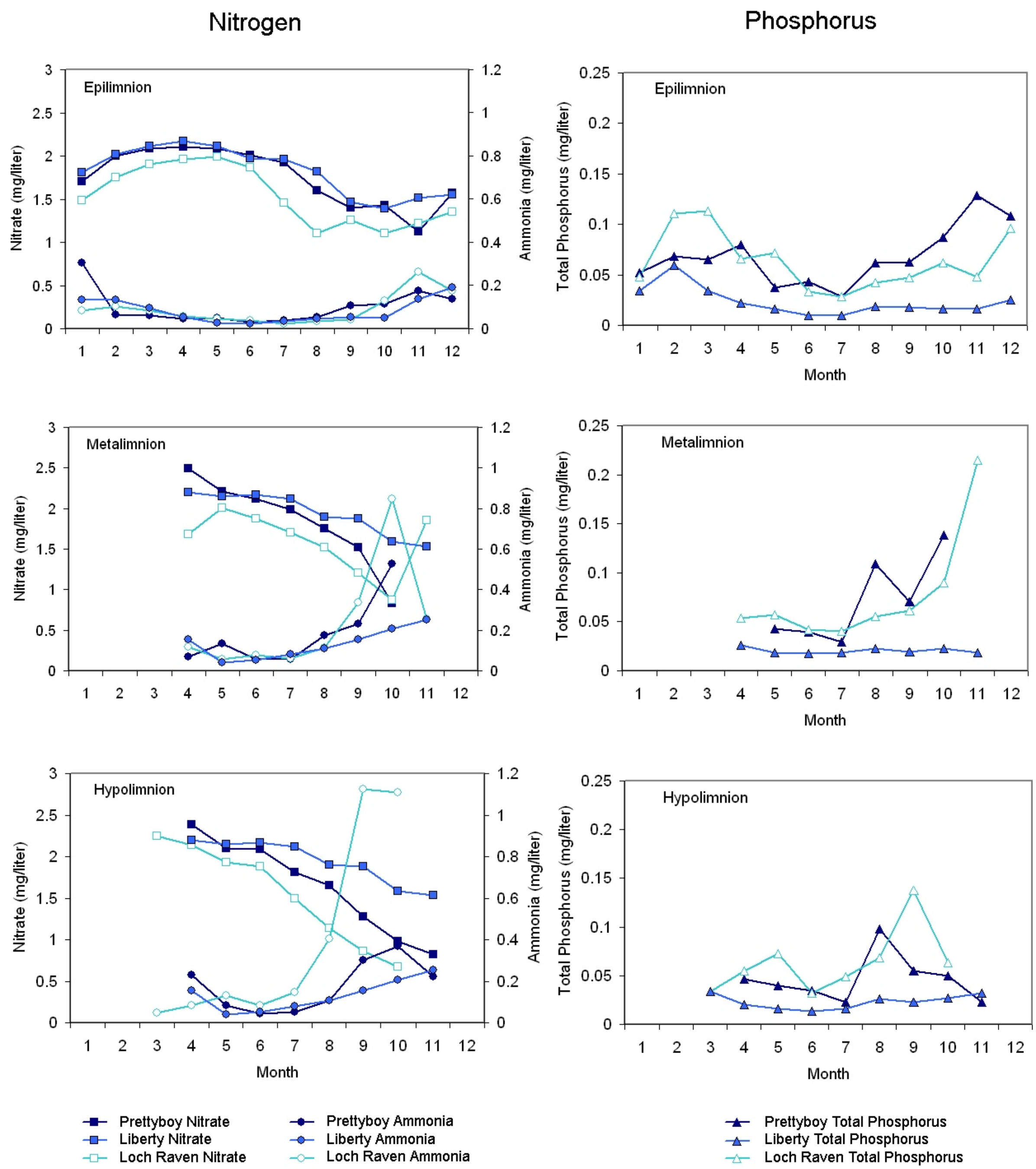


Figure 5. Monthly means of water column transparency (Secchi depth), turbidity, phytoplankton biomass (estimated with chlorophyll *a*), and water color. Minimum and maximum monthly values for Secchi depth and turbidity are also shown.

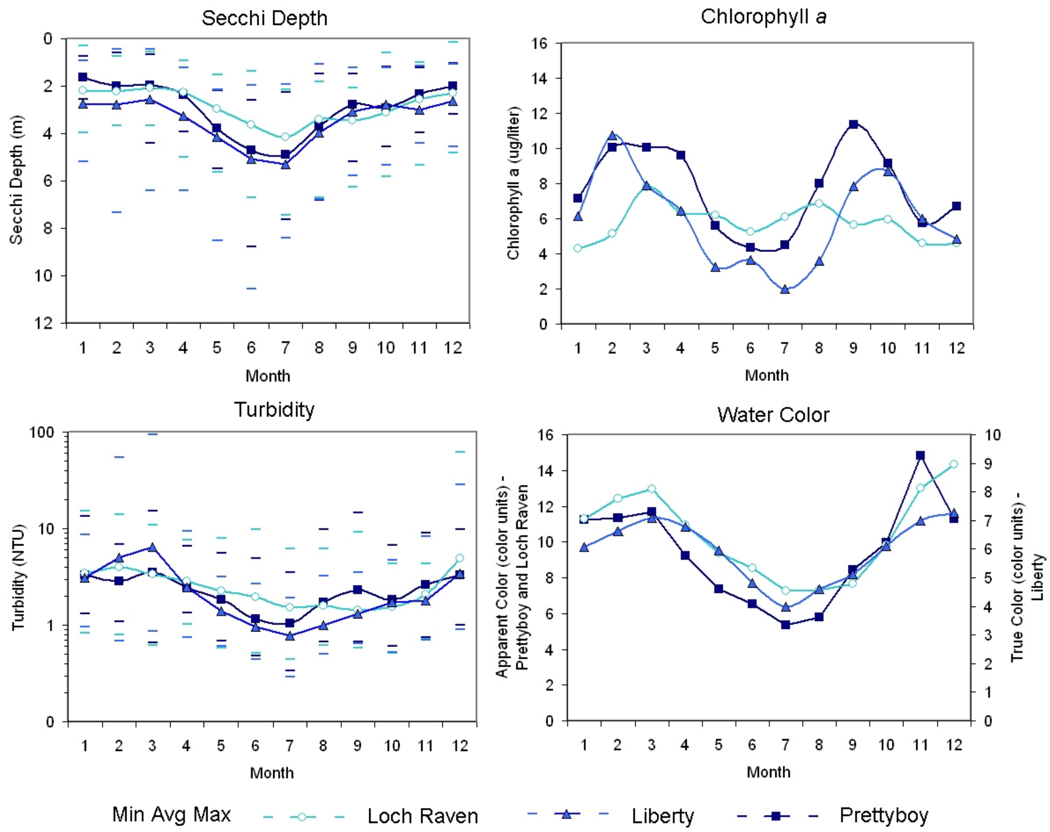


Figure 6. Depth profiles of the monthly minimum and maximum dissolved oxygen (DO) concentrations in the three reservoirs for January 1992 - July 2004.

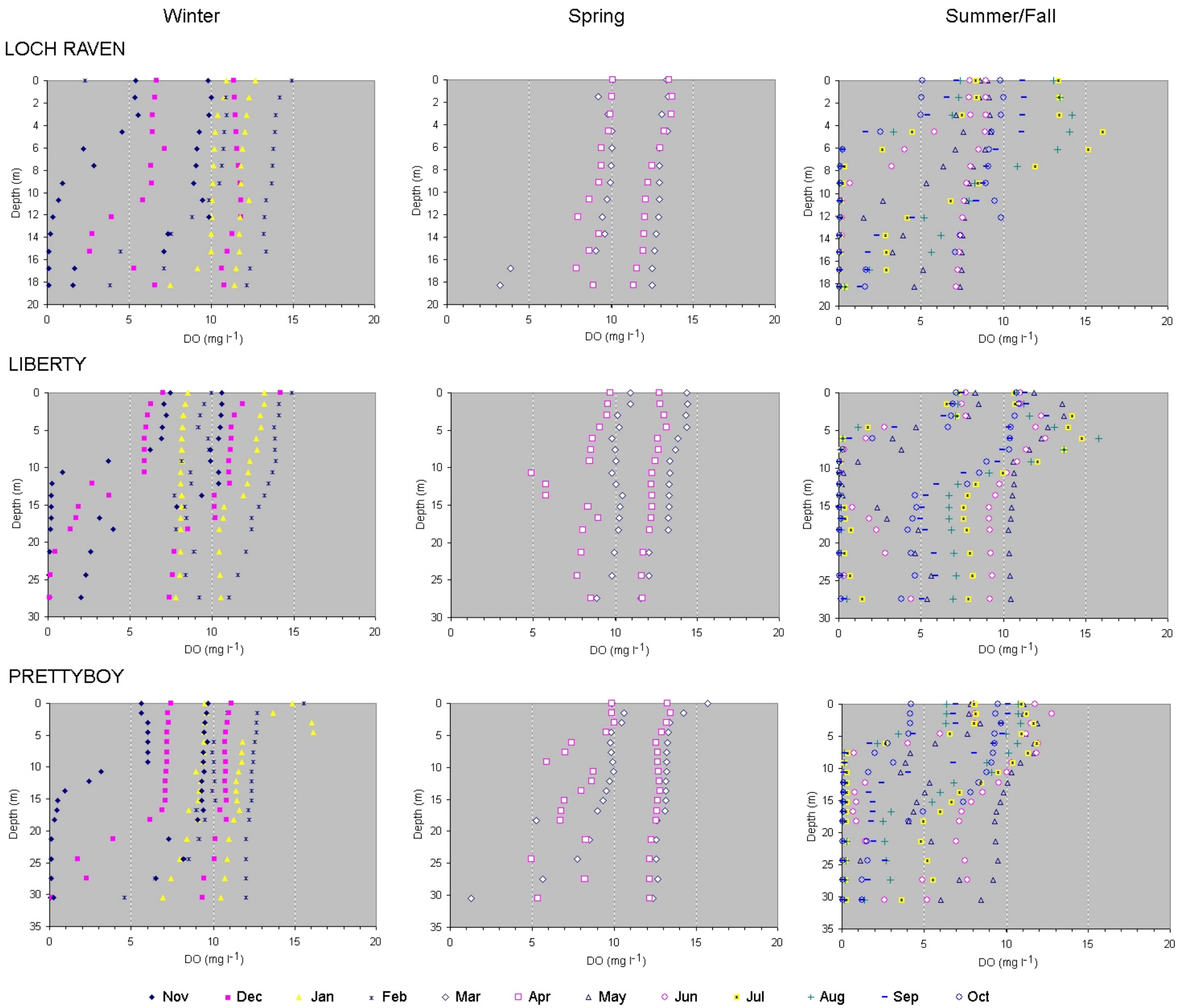


Figure 7. Depth profiles of the monthly minimum and maximum pH values in the three reservoirs for January 1992 - July 2004.

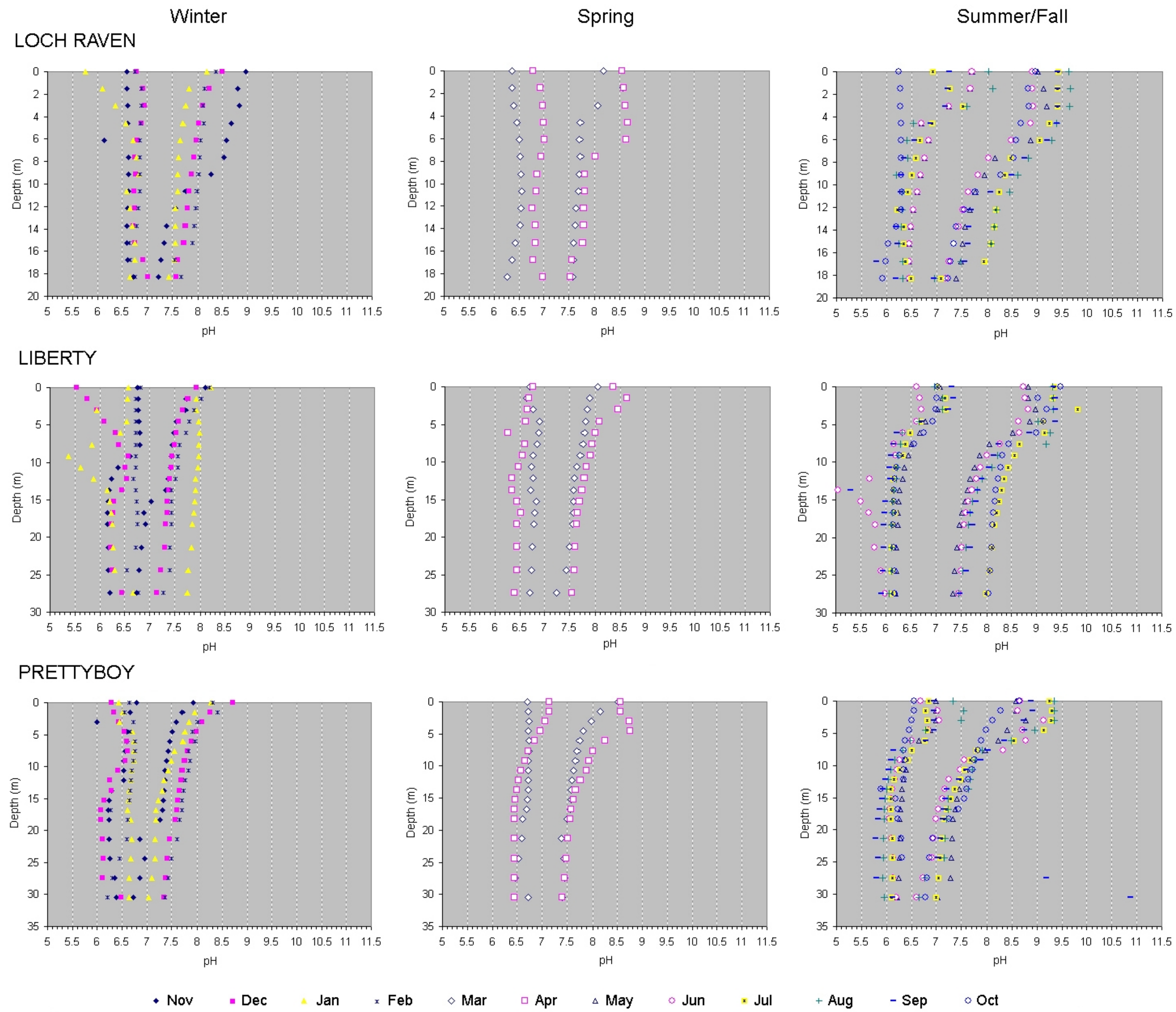


Figure 8. Comparison of water quality classification thresholds. Vertical lines in each panel indicate this study's water quality classification thresholds for transparency (Secchi depth in meters), total phosphorus (mg l^{-1} TP), and dissolved inorganic nitrogen (mg l^{-1} NO_3+NO_2+NH_4). Horizontal bars indicate the range of values in the literature that are used to classify the general trophic status of lakes and reservoirs. Transparency classes are derived from Secchi depth ranges in Wetzel (2001, Table 13-18). Total phosphorus classes are derived from TP ranges in Lampert and Sommer (1997, pg 310-314). These ranges are comparable to those provided by Wetzel (2001, Table 13-18), and they accommodate detection limits in the reservoir data (indicated on the x-axis by triangles). Dissolved inorganic nitrogen classes are derived from experimentally determined phytoplankton growth-limitation thresholds for DIN (Fisher and Gustafson 2003), and accommodate detection limits for the different components of DIN in the reservoir data (triangles along x-axis). Ranges for total nitrogen (TN) are typically used for trophic classification (e.g., Wetzel 2001, Table 13-18). However, DIN classes rather than total nitrogen (TN) classes were developed for this study because reservoir TN data were not available. A small fraction of the DIN data may be incorrectly classified as "poor" instead of "better" because of the relatively high NO_3 detection limit in some of the data. Overall, the reservoirs were heavily enriched with nitrogen, and 98.9% of nitrate concentrations were greater than the 0.5 mg l^{-1} detection limit.

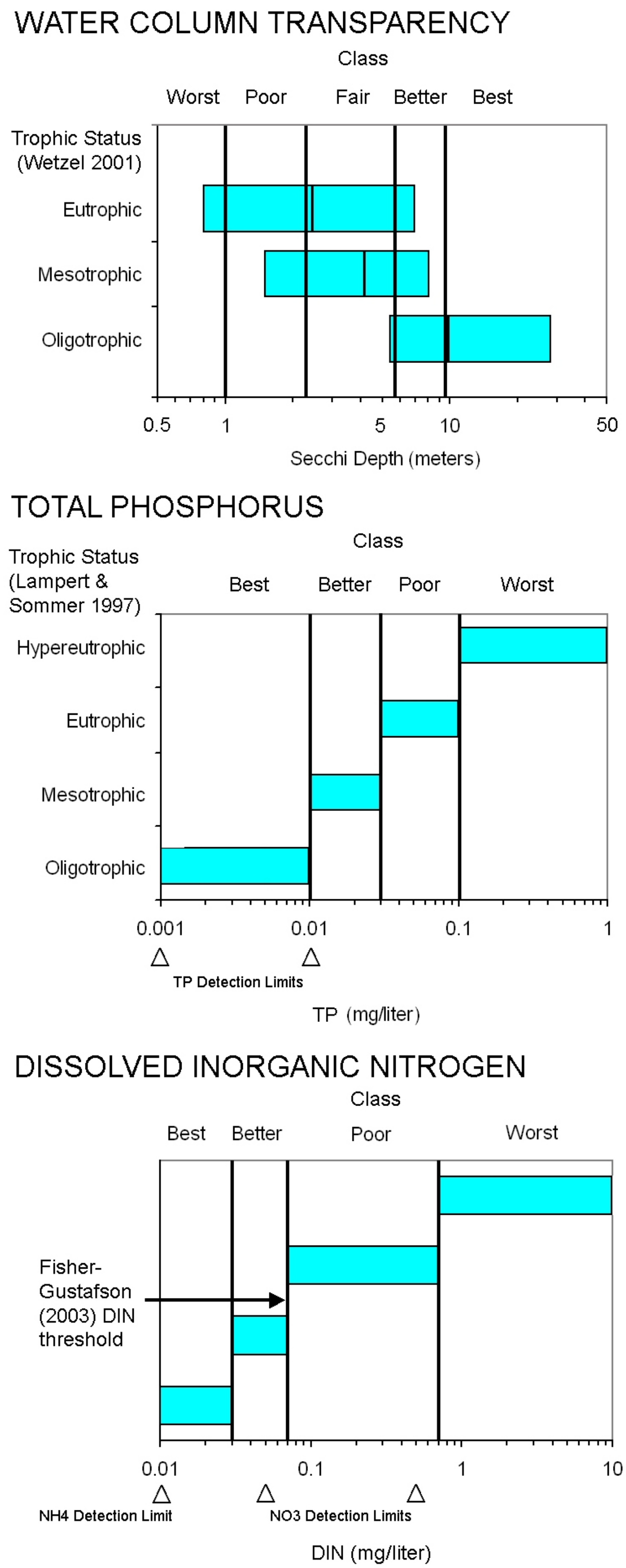


Figure 9. Average monthly frequency of each water quality category in the whole water column (unstratified periods) and epi- and metalimnion (stratified periods) of the three Baltimore reservoirs.

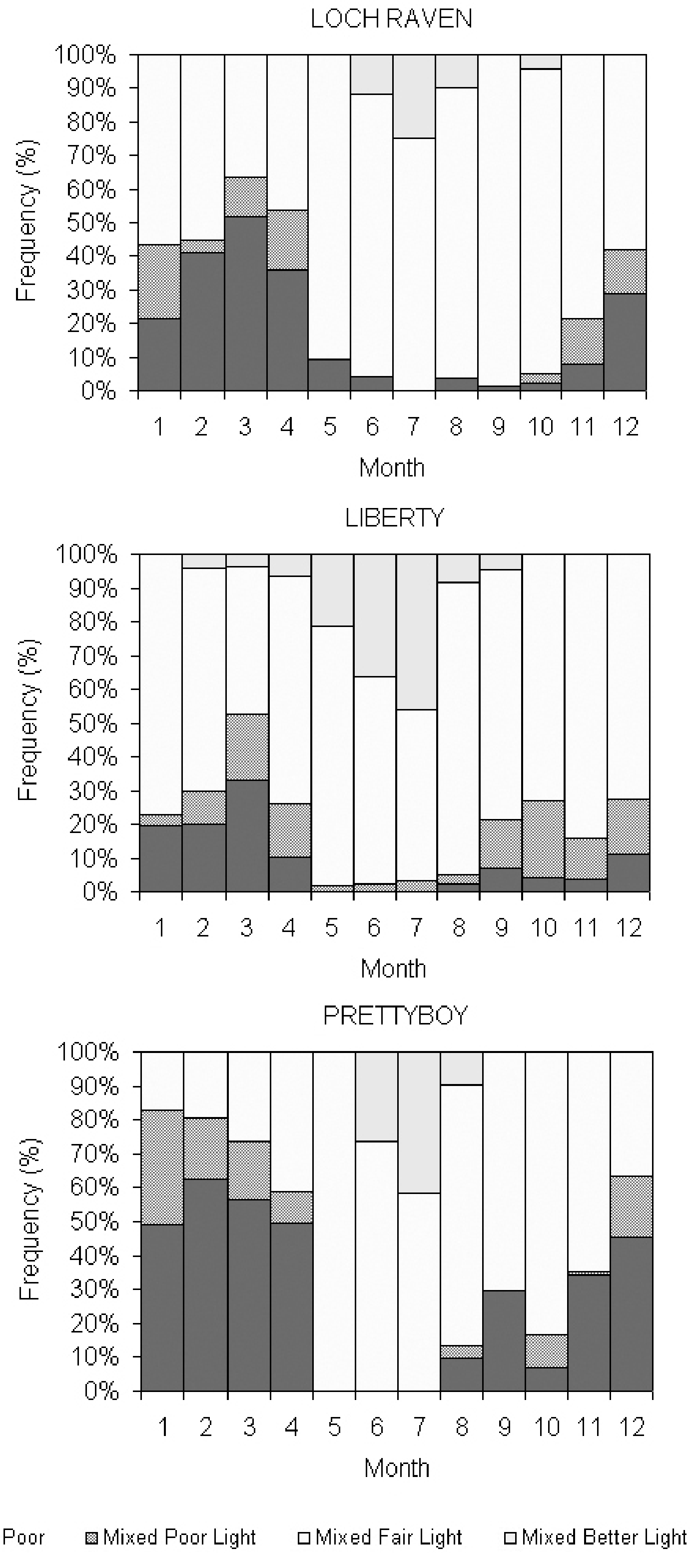


Figure 10. Chlorophyll *a* distributions in the Loch Raven, Liberty, and Prettyboy reservoir water quality categories for non-stratified and stratified periods. The 5th%, 25th%, median, 75th%, and 95th% are shown. Values above 10 µg chl *a* l^{-1} (red line) are considered elevated levels (ELs). The non-stratified period is primarily between November and April, and temperature gradients indicate the entire water column mixes. The stratification period occurs primarily between May and October. A metalimnion initially forms high in the water column, and is moved down during summer and fall (Fig. 2).

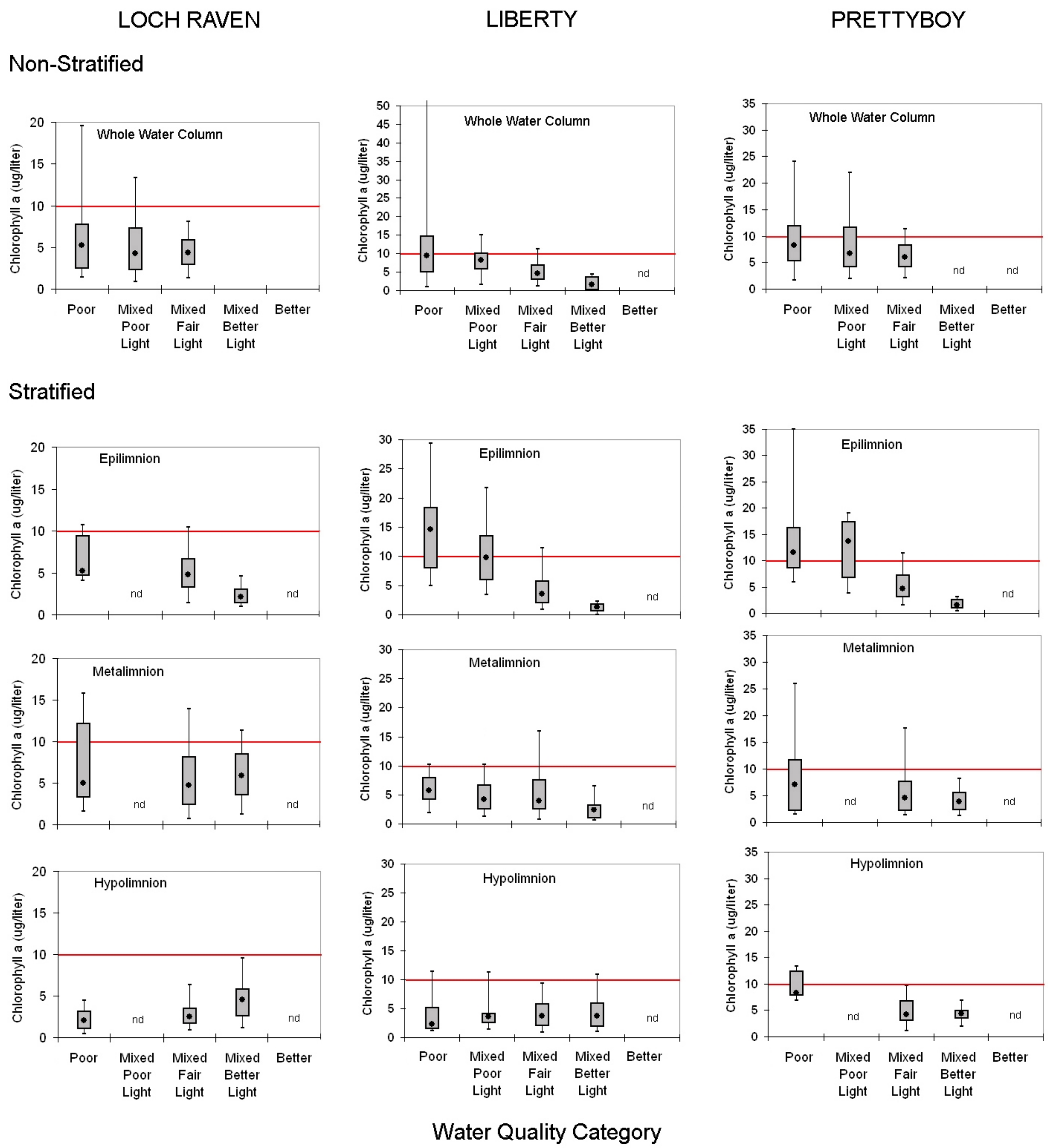


Figure 11. Frequency of elevated chlorophyll *a* levels (>10 µg l^{-1}), in A) water quality categories derived using the Secchi depth, TP, and DIN thresholds in Table 2, and B) abbreviated water quality categories derived using only the Secchi depth and TP thresholds. Key: cross-hatched bars, non-stratified water column; light gray bars, epilimnion; dark gray bars, metalimnion; black bars, hypolimnion; "-", less than 8 data points; "0", 0% frequency of elevated chlorophyll *a* levels.

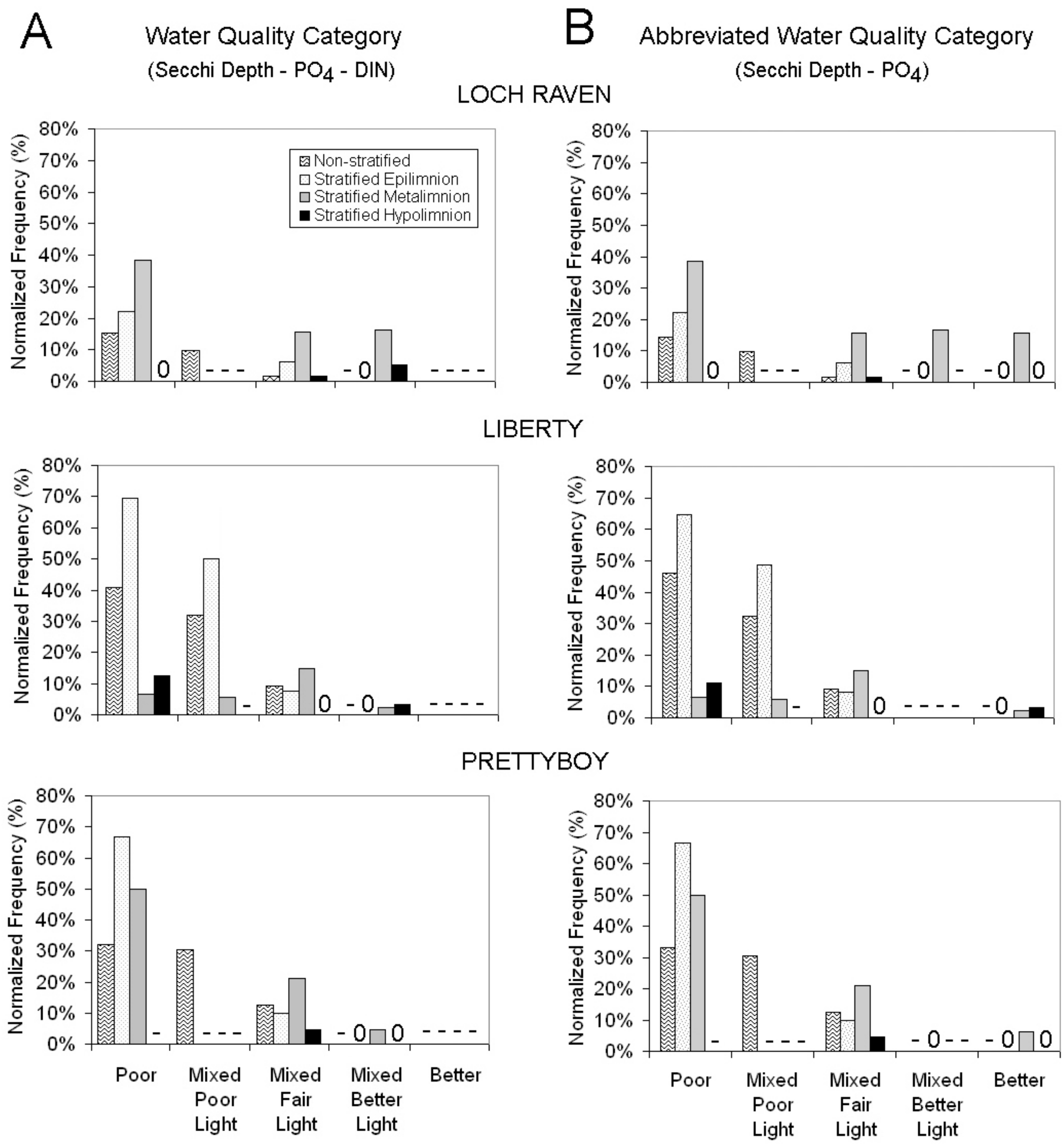
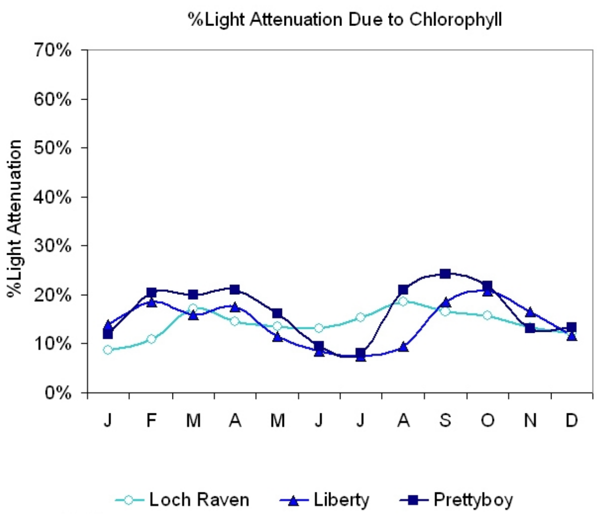
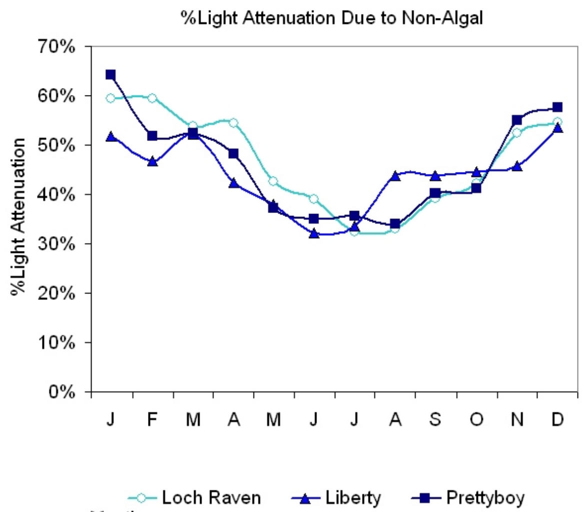


Figure 12. Monthly average %light attenuation due to algae, as represented by chlorophyll *a*, and by non-algal constituents, excluding water itself. See text for details.



Month	Loch Raven	Liberty	Prettyboy
J	8.8%	14.0%	12.0%
F	11.0%	18.5%	20.3%
M	17.1%	15.9%	20.1%
A	14.6%	17.5%	20.9%
M	13.6%	11.6%	16.1%
J	13.2%	8.5%	9.5%
J	15.3%	7.5%	8.0%
A	18.6%	9.6%	20.9%
S	16.6%	18.5%	24.1%
O	15.8%	20.8%	21.8%
N	13.3%	16.5%	13.1%
D	12.1%	11.7%	13.2%
Overall	14.1%	14.2%	16.7%



Month	Loch Raven	Liberty	Prettyboy
J	59.3%	51.9%	64.2%
F	59.5%	46.8%	51.7%
M	53.9%	52.1%	52.5%
A	54.4%	42.3%	48.3%
M	42.6%	38.0%	37.2%
J	39.1%	32.2%	34.9%
J	32.4%	33.5%	35.7%
A	32.9%	43.7%	34.0%
S	39.1%	43.9%	40.2%
O	42.3%	44.5%	41.3%
N	52.3%	45.8%	55.0%
D	54.7%	53.6%	57.6%
Overall	46.9%	43.2%	46.0%

Figure 13. Comparisons of minimum (-), average (o), and maximum (-) values of the %light attenuation due chlorophyll *a* (%η_{CHL}) and %light attenuation due non-algal constituents (%η_{OTHER}) *versus* Secchi depth. %η_{OTHER} excludes the estimated attenuation due to water itself, or η_{H2O} = 0.19 m^{-1}. Line indicates the 10-period moving average of the averages.

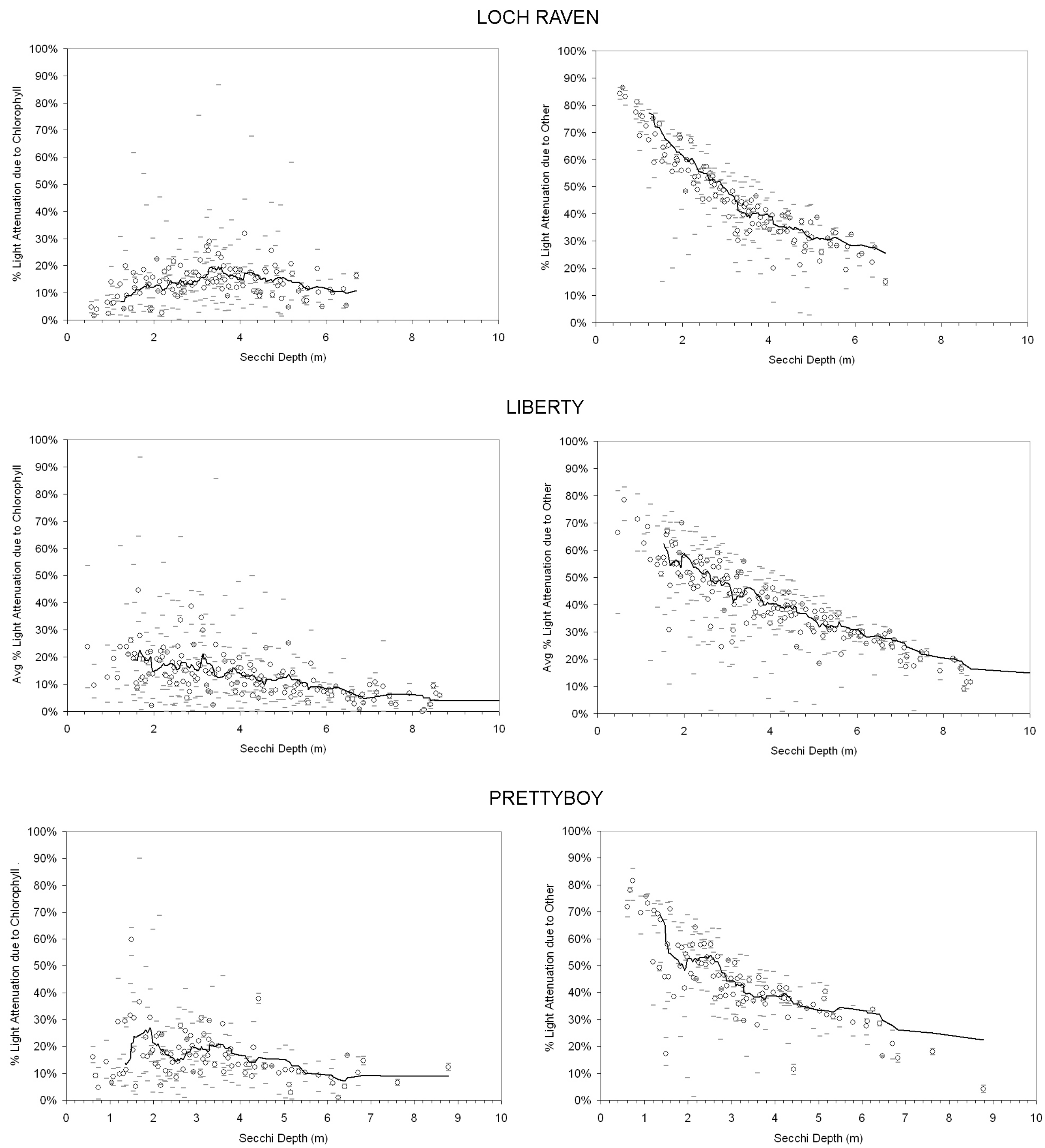


Figure 14. Chlorophyll *a* concentrations at different TP concentrations in each of the Baltimore reservoirs. Gray bar indicates range (5^{th}% - 95^{th}%) of chlorophyll *a* concentrations within each TP interval (<0.01 mg l^{-1}, 0.01-0.03 mg l^{-1}, etc.); solid circle indicates median.

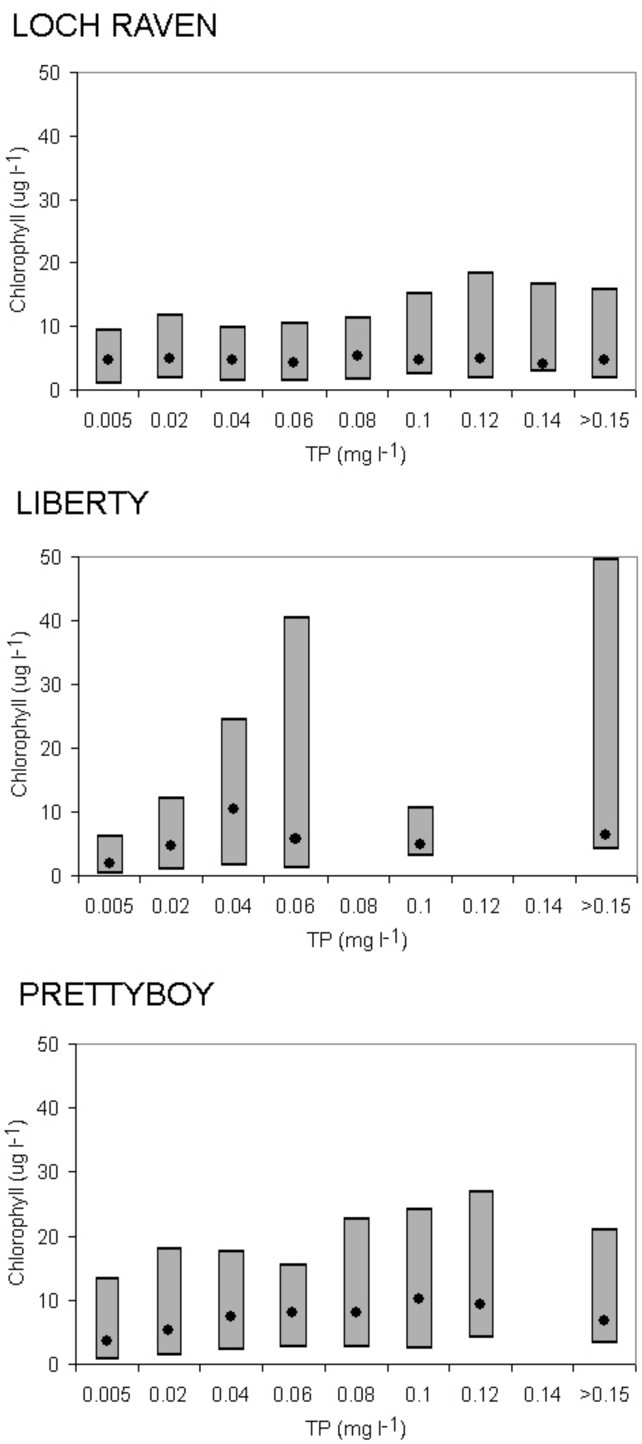


Figure 15. Frequency of elevated levels of chlorophyll *a* (%) in different η_{OTHER} (extinction coefficient of all non-algal matter excluding water itself) and depth intervals, for TP concentrations of $\leq$0.01 mg l^{-1} (◇, “best” class), >0.01 - <0.03 mg l^{-1} (□, “better” class), 0.03 - 0.10 mg l^{-1} (●, “poor” class), and >0.10 mg l^{-1} (▲, “worst” class). Numbers above each panel indicate number of algal blooms (>30 µg chl *a* l^{-1}) observed at that η_{OTHER}. High values of η_{OTHER} correspond to high concentrations of non-algal matter such as detritus, dissolved organic matter, and suspended inorganic sediments. *, includes 8 data points from η_{OTHER} = 0.3-0.4 m^{-1}. See text for further details.