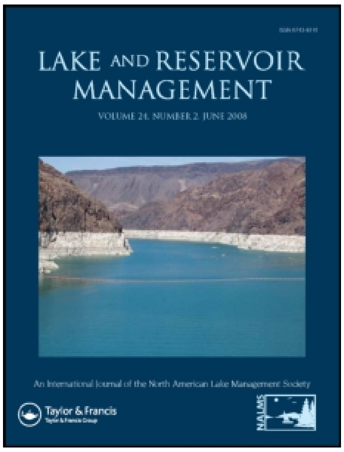

Lake and Reservoir Management
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t905619022

NOTE: Empirical estimation of non-chlorophyll light attenuation in Missouri reservoirs using deviation from the maximum observed value in the Secchi-Chlorophyll relationship

John R. Jones[a]; Jason A. Hubbart[a]
[a] School of Natural Resources, Anheuser-Busch Natural Resources Building, University of Missouri, Columbia, MO

First published on: 15 March 2011

Lake and Reservoir Management, 27:1–5, 2011

ISSN: 0743-8141 print / 1040-2381 online
DOI: 10.1080/07438141.2011.554962

NOTE

Empirical estimation of non-chlorophyll light attenuation in Missouri reservoirs using deviation from the maximum observed value in the Secchi-Chlorophyll relationship

Abstract

A quadratic reference line delineates the maximum observed Secchi transparency across the measured range of algal chlorophyll (0.7–297 μg/L) in Missouri reservoirs. Deviations below maximum Secchi transparency were common (median = 45% of maximum, interquartile range between 35 and 57%) and are characteristic of water bodies with mineral turbidity. Subtracting the reciprocal of maximum Secchi from the reciprocal of measured Secchi provides an estimate of non-chlorophyll light attenuation (NCLA, m^{-1} = [1/Secchi] – [1/maximum Secchi]). Analyses of several datasets show most cross-system variation in this empirical estimate of NCLA is accounted for by non-algal seston measured gravimetrically and as clay-sized particles. Residual variation is attributed to characteristics of the algal community and color. This simple approach can be applied directly, or with modification, to estimate NCLA in lakes and reservoirs when measurements of mineral particulates are not available. The degree to which response variables, such as Secchi transparency, are less than the maximum is fundamental to our understanding of lake process and their management.

Key words: chlorophyll, light attenuation, Missouri reservoirs, non-algal seston

Limnologists have long recognized that mineral turbidity, measured as non-algal seston (NAS), reduces transparency in lakes and reservoirs and uncouples the relationship between Secchi depth (m) and algal biomass. In this research note we present an equation delineating maximum observed Secchi transparency in Missouri reservoirs across the measured range of algal chlorophyll (Chl; μg/L) and show that deviations below the maximum provide an empirical estimate of non-chlorophyll light attenuation (NCLA; m^{-1}). Using regression and correlation (p values < 0.01), we compared values of NCLA with gravimetric measurements of NAS (mg/L; a combination of nonvolatile suspended solids [NVSS] and the weight of fine particulates in the filtrate, after Knowlton and Jones 2000) and the volumetric concentration of suspended particle size class (μL/L) measured by laser diffraction.

Walker's original work on this topic provided the basis for our inquiry (Walker 1982). Using reservoir data, Walker proposed an empirical relationship to separate light extinction into components determined by Chl and related substances from non-algal turbidity (NAT; m^{-1} = [1/Secchi, m] – [0.025 m^2/mg·Chl mg/m^3]). Walker's equation is based on a fixed term for light attenuation by Chl and was formulated to predict Secchi depth in water with zero mineral turbidity; it does not separate Chl-specific scattering from absorption, consider the influence of algal cell size or vacuoles on transparency or differentiate the influence of dissolved organic matter and color from suspended solids (Edmondson 1980, Weidemann and Bannister 1986). For simplicity, these factors were considered part of the empirical estimate of NAT (Walker 1982). Walker's estimation is an algorithm in a widely accepted eutrophication model (BATHTUB; Walker 1999). It can be restricted to correspond with maximum transparency in a given dataset and has been used to assess non-algal conditions in specific lakes (Heiskary and Walker 1995) and regions (Smith 1990, Carney 2009).

For 232 Missouri reservoirs and oxbow lakes (1545 seasonal means from the dataset of Jones et al. 2008), an *ad hoc* fit suggests a quadratic reference line delineates the upper boundary of Secchi transparency (0.1– 6.5 m) observed across the range of mean summer Chl (0.7–297 μg/L; Fig. 1a). The line was fitted to the upper edge of the distribution using $\log_{10}$ Chl and $\log_{10}$ Chl^2 in stepwise regression to explain the nonlinear maximum in $\log_{10}$ Secchi:

$$\log_{10}\text{Secchi} = 0.90 - 0.29(\log_{10}\text{Chl}) - 0.13(\log_{10}\text{Chl})^2 \quad (1)$$

The intercept equates to a Secchi depth of 7.94 m, which approximates maximum transparency recorded in the least fertile and least turbid water bodies in our long-term sampling effort (Jones et al. 2008). On average, transparency in this dataset was 46% of maximum Secchi (median = 45%) with the interquartile range between 35 and 57%. Only 10% of the values were >68% of maximum Secchi.

This reference line may also have application beyond Missouri; it largely envelops the upper boundary of Secchi-Chl data from lakes and reservoirs in 5 Midwestern states (Fig. 1b; Knowlton and Jones 1993, Graham et al. 2004), and with greater scatter, lakes and reservoirs widely distributed throughout North America (Fig. 1c; Jones and Bachmann 1978). Variation around an upper limit is expected in distributions of this type (Kaiser et al. 1994), and natural lakes with low mineral turbidity and color would likely fall near, or exceed, maximum Secchi observed in Missouri reservoirs.

Empirical estimates of NCLA are measured as the deviation below maximum Secchi at a given Chl value. The calculation parallels that of Walker (1982); values are determined using the quadratic equation (equation 1) to calculate maximum Secchi at a given Chl value (back-transformed; Fig. 1a) and

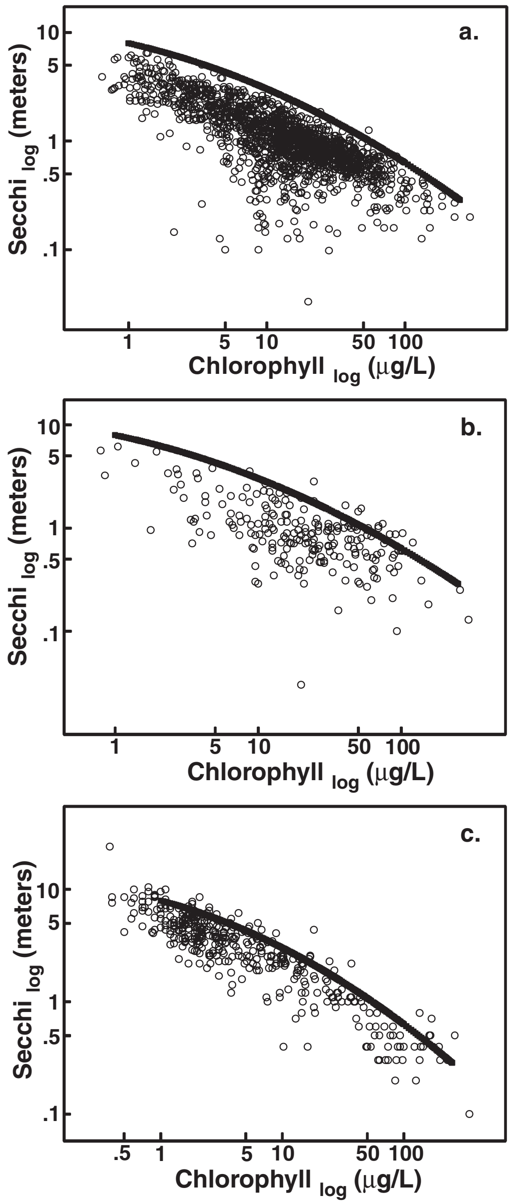

Figure 1.-Seasonal mean (May–Aug) Secchi depth and chlorophyll (Chl; n = 1546) from 232 Missouri reservoirs and oxbow lakes (panel a). The quadratic upper boundary on Secchi transparency was fitted *ad hoc* and is described by the equation: $\log_{10}$ Secchi = 0.90 – 0.29·($\log_{10}$ Chl) – 0.13·($\log_{10}$ Chl)^2. The upper boundary on Secchi is also plotted with data from 5 Midwestern states (from Knowlton and Jones 1993, Graham et al. 2004; panel b) and with North American lakes and reservoirs (Jones and Bachmann 1978; panel c).

subtracting its reciprocal from the reciprocal of measured Secchi:

$$\text{NCLA}(\text{m}^{-1}) = [1/\text{Secchi}] - [1/\text{maximum Secchi}] \quad (2)$$

Among seasonal means in this analysis (n = 1545), values of NCLA averaged 0.75 m^{-1} (median = 0.52 m^{-1}) with an interquartile range between 0.29 and 0.87 m^{-1}. Only 10% of the values were <1 m^{-1}. These values, based on deviation from the potential maximum, are largely attributed to mineral particulates and characteristics of the algal community because the influence of colored dissolved organic matter on transparency is modest in Missouri reservoirs (Jones et al. 2008, Watanabe et al. 2009).

Interestingly, we found that restricting Walker's formula to a maximum Secchi transparency of 7.9 m ($\alpha = 0.126$ m^{-1}) and reducing the slope parameter to 0.015 m^2/mg Chl (results not shown) provides an upper boundary and attenuation estimates that closely match our NCLA values.

The correlation between NCLA and our mass measurements of NAS was strong and positive (r = 0.88, n = 1546). Between the 2 fractions composing NAS, NCLA was more strongly correlated with the particulates measured as NVSS (r = 0.85) than fine materials in the filtrate (r = 0.72). After square root transformation to account for the distribution pattern in both variables, 82% of variation in NCLA is

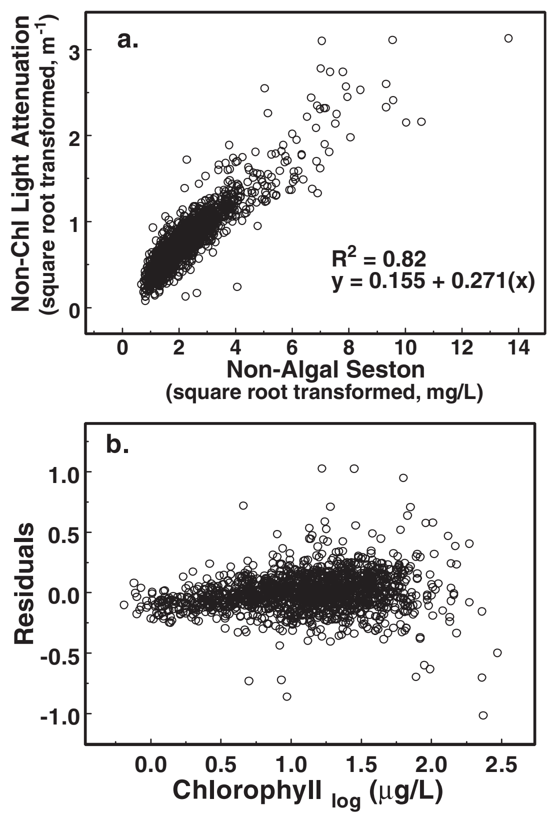

Figure 2.-Empirical estimates of non-chlorophyll light attenuation (NCLA; m^{-1}), described in the text, regressed on 1546 seasonal mean values of non-algal seston (NAS, mg/L) in Missouri reservoirs (both variables square root transformed; panel a). Residual estimates from the regression analysis in panel are plotted against seasonal mean chlorophyll values from the dataset (log transformed; panel b).

Table 1.-Secchi depth expressed as a percent of the upper limit at a given chlorophyll value were binned in quartiles (< 25%, 25 < 50%, 50 < 75% and > 75% of maximum transparency, formula described in the text). Within each bin are presented the number of observations, and the median values for % of maximum transparency (% max), Secchi depth, Chlorophyll (Chl), Ratio of Chl/Total Phosphorus, non-algal light attenuation (NCLA), and non-algal seston (NAS). For data within each bin, the coefficient of determination (R^2) for the regression of NCLA on NAS (square root transformed) is shown.

			Median values					
% of Maximum Secchi depth	n	% max. SD	Secchi Depth (m)	Chl μg/L	Ratio Chl/TP	NCLA m^{-1}	NAS mg/L	R^2 NCLA on NAS
< 25%	164	17.5	0.47	10.9	0.18	1.75	16.4	0.73
25 < 50%	788	39.5	0.98	12.9	0.35	0.61	4.8	0.73
50 < 75%	518	58.4	1.22	18.4	0.50	0.32	2.6	0.72
>75%	75	80.8	1.57	23.3	0.62	0.11	2.1	0.49

explained by NAS in the Missouri dataset (Fig 2a). Based on visual inspection of residuals from regressing NCLA on NAS, there was no bias in the relationship across the range of Chl (Fig. 2b).

Among seasonal means with measured Secchi <75% of maximum, NAS explained more than 70% of variation in calculated NCLA (data were binned into quartiles =<25%, 25 < 50%, 50 < 75% and >75% of maximum transparency at a given Chl value; Table 1). Among observations with Secchi >75% of maximum, however, NAS accounted for about half of variation in NCLA (Table 1). Observations in this category generally had larger Chl and Chl/TP ratios, smaller NAS and NVSS values, and greater transparency than the remainder of the dataset (Table 1). Presumably, in samples with modest mineral turbidity, characteristics of the algal community and color would be influential in determining differences between maximum and observed transparency (Edmondson 1980). This comparison suggests NCLA is more strongly related to NAS in cases where mineral turbidity would most likely be a factor.

As a further test, we applied the NCLA calculation to a dataset with weekly collections from 15 northern Missouri reservoirs (49 weeks between Jan and Dec 2004, n = 725). This evaluation differs from the previous analysis because the data are individual observations, not seasonal means, and include seasons other than summer. Despite these differences, the quadratic reference line generally delineates the upper boundary of Secchi transparency in the seasonal data (Fig 3a) with some observations located above the upper limit, particularly among samples with Chl > 25 μg/L. Variation is expected in this comparison because the reference line was developed using seasonal means, and the aggregation step would dampen extreme observations in the overall pattern (Jones et al. 1998, Jones and Knowlton 2005). Regardless, only 3% of values resulted in negative NCLA estimates (from samples with observed transparency greater than the upper boundary), and half of these differences were quite small.

Among these weekly collections, NAS accounted for 74% of cross-system variation in NCLA (square root transformed), and the pattern between NCLA and NAS matched that of seasonal means from Missouri reservoirs (Fig. 3b). Noteworthy, when the dataset was divided into summer (May

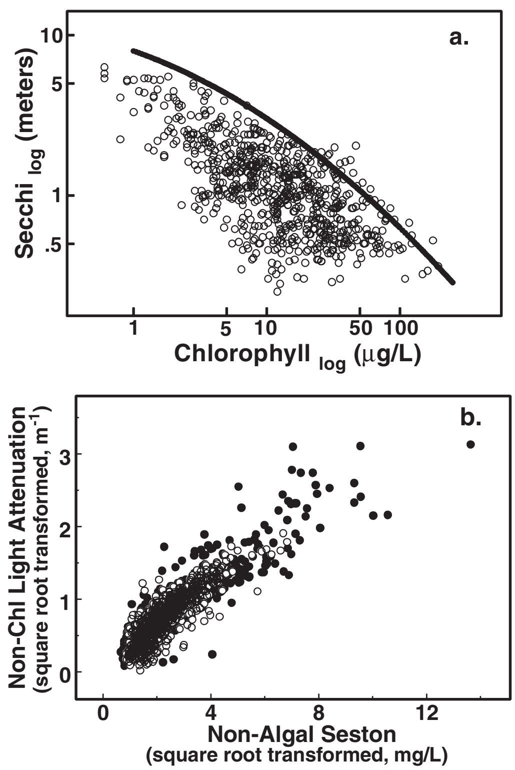

Figure 3.-Secchi depth and chlorophyll data from 15 north Missouri reservoirs sampled weekly between Jan and Dec 2004 (n = 49 weeks and 734 samples). The upper boundary on Secchi is described in the text and shown in Fig. 1 (panel a). Empirical estimates of non-chlorophyll light attenuation (NCLA; m^{-1}), described in the text, and non-algal seston (NAS; mg/L) from 15 northern Missouri reservoirs sampled between Jan and Dec 2004 (n = 734; open circles) overlaid on these same variables from 1546 Missouri reservoirs shown in Fig. 2a (dark circles).

through Aug samples, n = 269) and the remainder of the year (n = 456), the range in NCLA and NAS was similar in both periods (from <1 to ∼3.4 m^{-1} for NCLA and <1 to ∼45 mg/L for NAS); during the 2 periods NAS accounted for 70 and 75% of variation in NCLA, respectively (square root transformed). This finding supports the hypothesis that NCLA calculations are correlates of NAS during nonsummer seasons.

The optical properties of suspended matter are strongly related to surface area and may determine light attenuation more than their mass concentration (Davies-Colley and Smith 2001). In 68 Missouri reservoirs sampled in 4 successive statewide collections between May and August 2009 (n = 272; after Jones et al. 2008) empirical estimates of NCLA (median value = 0.61 m^{-1}, interquartile range between 0.35 and 1.0 m^{-1}) were positively correlated with NAS (r = 0.84) and its 2 fractions (r = 0.79 with NVSS and 0.77 with fine particulates, square root transformed). Values of NCLA were similarly correlated with the volumetric concentration of clay-sized particles measured by laser diffraction (Sequoia Scientific); the correlation with particles of 2.06 and 2.43 μm (r = 0.78 and 0.75, respectively, square root of μL/L, n = 272) was slightly stronger than with particles of 2.87 μm (r = 0.70). Correlations were much weaker with particles of increasing size.

Median Secchi transparency increased among the 68 reservoirs from 0.78 m in May to 0.98 m in August, and the strength of the cross-system correlation between NCLA and particle concentration showed a seasonal change during summer. Values of NCLA were most strongly correlated with clay-sized particles during the first 3 summer collections (r = 0.73–0.88, square root transformed; n = 68 per sampling) and with measurements of NAS (r = 0.88–0.93, square root transformed). Among the final samples from summer 2009 correlations between NCLA and clay particles were significant but weaker (r =< 0.63), as was the correlation with NAS (r = 0.58).

Between the first and final collection in 2009, both median NCLA and NAS declined by some 40%, and median Chl values increased by 30% with a 22% increase in the median ratio of Chl/TP. Across the 4 sample collections, observed Secchi increased from 38% of maximum to 49%; this seasonal pattern is consistent with previous observations showing mineral turbidity declines and transparency increases in late summer (Jones and Knowlton 2005) and supports the assumption that small particles are an important component of non-algal seston (Knowlton and Jones 2000). It is beyond the scope of this research note to address the relationship between NAS and particle size classes.

This analysis expands and advances previous studies showing variation in NAS largely determines light attenuation in Missouri reservoirs (Knowlton and Jones 2000, Jones et al. 2008). It emphasizes the concept of maximum Secchi transparency observed at a given Chl value in lakes and reservoirs rather than distribution pattern in the 2 variables described by regression (Jones and Bachmann 1978). We show deviations below the upper boundary are easily calculated and represent observed transparency as a proportion of the maximum. These deviations provide empirical estimates of NCLA that are broadly attributable to factors associated with NAS measured gravimetrically and by particle analysis.

Why, when and the degree to which response variables such as Secchi transparency are less than maximum is fundamental to our understanding of lake process and their management (Kaiser et al. 1994, Jones and Knowlton 2005, Jones et al. 2008). Our equations are empirical; the physical properties of the complex relationships determining transparency are addressed by others (e.g., Weidemann and Bannister 1986, Knowlton and Jones 2000, Davies-Colley and Smith 2001, Effler et al. 2002). Preliminary evaluation suggests the quadratic reference line delineating maximum Secchi transparency in Missouri reservoirs (Fig. 1a) may apply to other lake systems and seasons other than summer. In datasets where the upper Secchi boundary (equation 1) does not adequately describe maximum transparency the equations can be modified using our *ad hoc* approach or by altering the slope parameter and restricting maximum transparency in Walker's formula. Regardless, this approach can be used to estimate NCLA in datasets where measurements of mineral particulates are not available to interpret its influence on transparency and other lake processes (Dzialowski et al., 2011).

John R. Jones and Jason A. Hubbart

School of Natural Resources, Anheuser-Busch Natural Resources Building, University of Missouri, Columbia MO 65211-7240
Corresponding author: jonesj@missouri.edu

Acknowledgments

This work was funded by the Missouri Department of Natural Resources and the Missouri Agricultural Experiment Station. We thank Matthew Knowlton, Daniel Obrecht, Joshua Millspaugh and Jennifer Graham for advice and technical assistance, Bob Carlson and anonymous reviewers for helpful suggestions.

References

Carney E. 2009. Relative influence of lake age and watershed land use on trophic state and water quality of artificial lakes in Kansas. Lake Reserv Manage. 25:199–207.

Davies-Colley RJ, Smith DG. 2001. Turbidity, suspended sediment, and water clarity: A review. J Am Water Resour Assoc. 37:1085–1101.

Dzialowski AR, Smith VH, Wang S-H, Martin MC, deNoyelles FJ. 2011. Effects of non-algal turbidity on cyanobacterial biomass in seven turbid Kansas reservoirs. Lake Reserv Manage. 27: 6–14.

Edmondson WT. 1980. Secchi disc and chlorophyll. Limnol Oceanogr. 25:378–379.

Effler SW, Perkins MG, Ohrazda N, Matthews DA, Gelda R, Peng F, Johnson DL, Stephczuk CL. 2002. Tripton, transparency and light penetration in seven New York reservoirs. Hydrobiologia.468:213–232.

Graham JL, Jones JR, Jones SB, Downing JA, Clevenger TE. 2004. Environmental factors influencing microcystin distribution and concentration in the Midwestern United States. Water Research. 38:4395–4404.

Heiskary SA, Walker WW Jr. 1995. Establishing a chlorophyll *a*goal for a run-of-the-river reservoir. Lake Reserv Manage. 11:67–76.

Jones JR, Bachmann RW. 1978. Trophic status of Iowa lakes in relation to origin and glacial geology. Hydrobiologia. 57:267–273.

Jones JR, Knowlton MF. 2005. Chlorophyll response to nutrients and non-algal seston in Missouri reservoirs and oxbow lakes. Lake Reserv Manage. 21:361–370.

Jones JR, Knowton MF, Kaiser MS. 1998. Effects of aggregation on chlorophyll-phosphorus relations in Missouri reservoirs. Lake Reserv Manage. 14:1–9.

Jones JR, Obrecht DV, Perkins BD, Knowlton MF, Thorpe AP, Watanabe S, Bacon RR. 2008. Nutrients, seston and transparency of Missouri reservoirs and oxbow lakes: An analysis of regional limnology. Lake Reserv Manage. 24: 155–180.

Kaiser MS, Speckman PL, Jones JR. 1994. Statistical models for limiting nutrient relations in inland waters. J Am Stat Assoc. 89:410–423.

Knowlton MF, Jones JR. 1993. Testing models of chlorophyll and transparency for Midwest lakes and reservoirs. Lake Reserv Manage. 8:13–16.

Knowlton MF, Jones JR. 2000. Non-algal seston, light, nutrients and chlorophyll in Missouri reservoirs. Lake Reserv Manage. 16:322–332.

Smith VH. 1990. Effects of nutrients and non-algal turbidity on blue-green algal biomass in four North Carolina reservoirs. Lake Reserv Manage. 6:125–131.

Walker WW. 1982. An empirical analysis of phosphorus, nitrogen, and turbidity effects on reservoir chlorophyll-*a* levels. Can Water Resour. J. 7:88–107.

Walker WW. 1999. Simplified procedures for eutrophication assessment and prediction: user manual. Prepared for Headquarters. Vicksburg (MS): US Army Corps of Engineers; Waterways Experiment Station; Instruction Report W-96–2.

Watanabe S, Knowlton MF, Vincent WF, Jones JR. 2009. Variability in the optical properties of colored dissolved organic matter in Missouri reservoirs. Verh Int Verein Limnol. 30:1117–1120.

Weidemann AD, Bannister TT. 1986. Absorption and scattering coefficients in Irondequoit Bay. Limnol Oceanogr. 31:567–583.