Nutrient – sestonic chlorophyll relationships in northern Ozark streams

Kirk Lohman and John R. Jones

Abstract: We investigated relationships between sestonic chlorophyll (Chl), total phosphorus (TP), and total nitrogen (TN) at 23 sites on 13 streams in the Missouri Ozarks. There was a strong curvilinear relationship between mean sestonic Chl and both mean TP (R^2 = 0.78) and mean TN (R^2 = 0.70). Both models were improved when catchment area was included with either TP (R^2 = 0.90) or TN (R^2 = 0.84). Limited to 17 sites without point source nutrient additions, the relationship between sestonic Chl and both TP and TN was linear. Including catchment area strengthened linear models with either TP (R^2 = 0.94) or TN (R^2 = 0.84). Land use (percent row crop or percent forest), together with catchment size, was also a good predictor of sestonic Chl in Ozark streams without point sources. When catchment area and TP or TN were used to predict sestonic Chl on specific dates following catastrophic flooding, models were less accurate than those based on long-term averages, but still explained 55–74% of the variance in sestonic Chl. Our results demonstrate that sestonic Chl is closely associated with nutrients and catchment area in Ozark streams and that nutrient – sestonic Chl models may have broad application in running waters.

Résumé : Nous avons étudié les relations entre la chlorophylle (Chl) sestonique, le phosphore total (PT) et l'azote total (AT) à 23 sites de 13 cours d'eau dans les monts Ozark, au Missouri. Nous avons observé une forte relation curvilinéaire entre, d'une part, la Chl sestonique moyenne, et, d'autre part, le PT moyen (R^2 = 0,78) et l'AT moyen (R^2 = 0,70). Les deux modèles ont été renforcés par la prise en considération de l'aire du bassin versant (PT : R^2 = 0,90; AT : R^2 = 0,84). En se limitant à 17 sites sans apports de nutriants de sources ponctuelles, nous avons observé une relation linéaire entre, d'une part, la Chl sestonique et, d'autre part, le PT et l'AT. La prise en considération de l'aire du bassin versant avait pour effet de renforcer les modèles linéaires tant avec le PT (R^2 = 0,94) qu'avec l'AT (R^2 = 0,84). L'utilisation des terres (pour cent de culture en lignes et pour cent de forêt), de pair avec la superficie du bassin versant, constituait aussi un bon prédicteur de la Chl sestonique dans les cours d'eau des Ozark sans sources ponctuelles. Quand l'aire du bassin versant et le PT et l'AT étaient utilisés pour prévoir la Chl sestonique à des dates précises après inondation catastrophique, les modèles étaient moins précis que ceux basés sur les moyennes à long terme, mais ils rendaient tout de même compte de 55 à 74% de la variance de la Chl sestonique. Nos résultats montrent que la Chl sestonique est étroitement associée aux nutriants et à l'aire du bassin versant dans les cours d'eau des Ozark, et que les modèles reliant les nutriants et la Chl sestonique peuvent avoir de vastes applications dans les eaux courantes.

[Traduit par la Rédaction]

Introduction

Based on data collected primarily from temperate streams in North America, Van Nieuwenhuyse and Jones (1996) showed that summer mean chlorophyll (Chl) concentration bore a lognormal curvilinear relationship with summer mean total phosphorus (TP) concentration with a precision similar to that found in lake models of similar scale (R^2 = 0.67). Using a bivariate model, stream catchment area had a significant effect on Chl at all levels of TP (R^2 = 0.73). Empirical models of this type provide a conceptual framework to evaluate theory about structural relationships driving ecosystem dynamics (Prairie et al. 1989). Presumably, increasing P leads to increased Chl in streams by directly stimulating algal growth in the water column and by stimulating the growth of benthic algae. This growth contributes to suspended algae during low-flow periods by sloughing excess cells and through scour and washout during high-flow events. The positive relationship of stream catchment area to sestonic Chl may stem from its correlation with hydraulic flushing rate (Dunne and Leopold 1978), which directly determines residence time of water in a particular system. In effect, washout rate of the algae declines with catchment size. Reduced washout may increase Chl by allowing more time for growth in suspension (Talling and Rzoska 1967) and by allowing the passive accumulation of cells dislodged from the streambed (Swanson and Bachmann 1976).

Empirical models of this type are used to make predictions about unsampled systems and are often used to evaluate the potential benefits of remedial management actions.

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Table 1. Mean values of TN, TP, sestonic Chl, benthic Chl, and catchment area for 23 sites in the northern Ozarks.

Site	TN ($\mu g \cdot L^{-1}$)	TP ($\mu g \cdot L^{-1}$)	Sestonic Chl ($\mu g \cdot L^{-1}$)	Benthic Chl ($mg \cdot m^{-2}$)	Catchment area (km^2)
Blythes Creek I*	8435	3093	20.3	199.4	8.22
Blythes Creek II*	985	350	5.4	247.5	41.58
Burris Fork	515	70	16.7	52.8	231.46
Clifty Creek	172	6	0.5	15.2	20.30
Little Maries River I	220	13	2.6	50.0	75.25
Little Maries River II	292	16	3.4	36.6	156.67
Little Saline Creek	527	29	1.8	68.7	33.35
Maries River I	282	16	1.8	57.8	72.96
Maries River II	302	18	2.1	42.2	239.47
Maries River III	345	17	3.4	55.4	484.77
Maries River IV	313	33	7.2	55.8	667.96
Morgan Branch	438	35	2.6	61.2	23.55
North Moreau Creek I	606	91	15.6	36.0	197.26
North Moreau Creek II*	927	227	41.4	58.4	419.19
North Moreau Creek III	765	119	29.0	33.9	864.57
Saline Creek	182	19	1.3	35.4	56.33
Smiths Creek	525	62	9.8	45.0	115.70
South Moreau Creek I	420	50	8.2	45.1	131.36
South Moreau Creek II	454	86	13.5	72.9	357.40
Straight Fork I*	4134	2136	44.6	90.8	15.29
Straight Fork II*	1242	474	15.3	115.8	44.10
Straight Fork III	514	82	11.2	79.2	125.26
Willow Fork*	2098	893	19.8	69.9	40.58

Note: Values represent the mean of samples collected over a 2-year period (1985–1986); n = 31–38 for all sites except Morgan Branch where n = 22. An asterisk indicates that the site is influenced by sewage treatment effluent.

These models are typically developed from point averages (seasonal means) obtained over a broad range of systems, and how well they will work in a specific region and at different time scales is unknown. To further evaluate the structural relationships between nutrients (TP and total nitrogen (TN)) and Chl in a specific region, we analyzed data from a suite of northern Ozark streams draining mixed agricultural catchments, some with point source inputs from small municipalities. The data were collected to evaluate the effects of nutrient enrichment on periphyton (Lohman et al. 1992). These streams are characterized by low nitrate concentrations and low N:P ratios. Nitrogen limitation of periphyton was demonstrated in one of the streams and is probably common throughout the northern Ozark region (Lohman et al. 1991). The study included a fortuitous natural experiment consisting of a catastrophic flood, followed by a prolonged flood-free period. Data from this period allowed us to examine whether the large-scale pattern of nutrient–Chl relationships operates at a time scale other than the seasonal mean.

Methods

Nutrient and algal data were collected March–November 1985 and 1986 at 23 sites on 13 streams located in the northern Ozark Plateau, Missouri. The methods and study sites were described by Lohman et al. (1992), and nutrient data reported in that publication are summarized in Table 1 for sites with and without point sources. We followed the approach of Lohman et al. (1992) and excluded samples collected during flood events from our analysis (n = 31–38 per site during the 2-year period). In this analysis, we also included data from Morgan Branch in the South Moreau Creek drainage (Lohman 1988); this site was sampled on 24 occasions. Rainfall of 30–40 cm within a 2-week period in September–October 1986 occurred throughout the northern Ozarks and streams at all study sites were at or near flood stage during the first week in October. Measurements were collected at 2-week intervals following the flood.

In an exploratory analysis, we determined that regional nutrient – sestonic Chl models did not differ between 1985 and 1986. For simplicity of presentation, we averaged samples across both years to provide single point averages for each site. This approach is consistent with empirical evaluations in limnology. All statistical analyses were conducted using $\log_{10}$-transformed values to help stabilize variance. Land cover data were expressed as the arcsin square root of the proportion of basin area. A $p < 0.05$ was used to determine statistical significance.

Results

Nutrient – sestonic Chl relationships

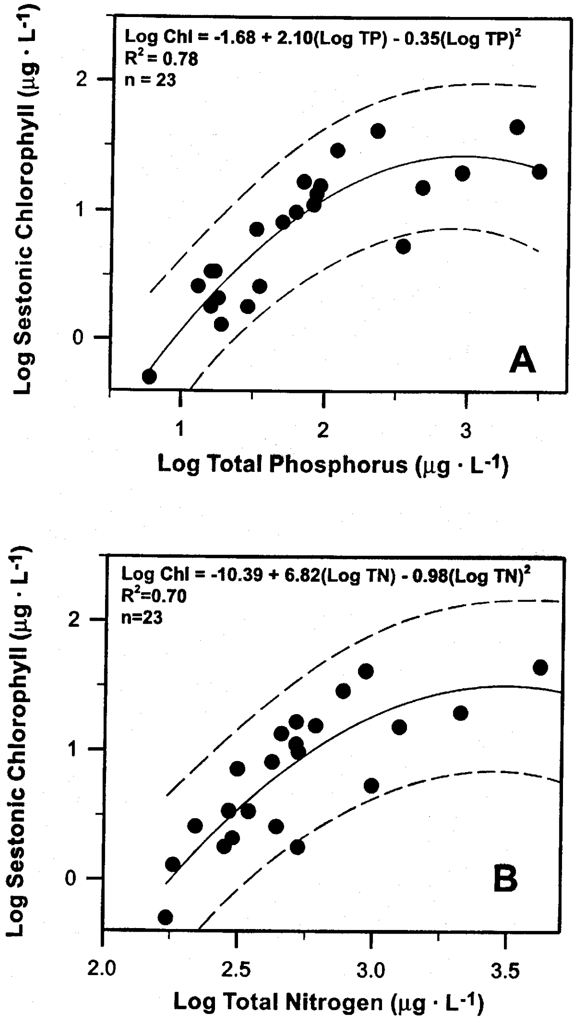
Among northern Ozark streams, log sestonic Chl showed a significant quadratic relationship with both TP and TN (Fig. 1):

$$(1) \quad \log \mathrm{Chl} = -1.68 + 2.10(\log \mathrm{TP}) - 0.35(\log \mathrm{TP})^2 \quad (R^2 = 0.78,\ F = 36.5,\ p < 0.001,\ n = 23)$$

$$(2) \quad \log \mathrm{Chl} = -10.39 + 6.82(\log \mathrm{TN}) - 0.98(\log \mathrm{TN})^2 \quad (R^2 = 0.70,\ F = 0.68,\ p < 0.001,\ n = 23).$$

The coefficients in the TP–Chl relationship for Ozark streams were virtually identical to those in the large-scale quadratic model of Van Nieuwenhuyse and Jones (1996, their eq. 1). The quadratic relationships of both TP and TN

Fig. 1. Relationship of sestonic Chl to (A) TP and (B) TN among 23 sites on streams in the northern Ozarks of Missouri. Points represent the average values of samples collected bimonthly between March and November 1985 and 1986. Broken lines are 95% confidence intervals for the populations.



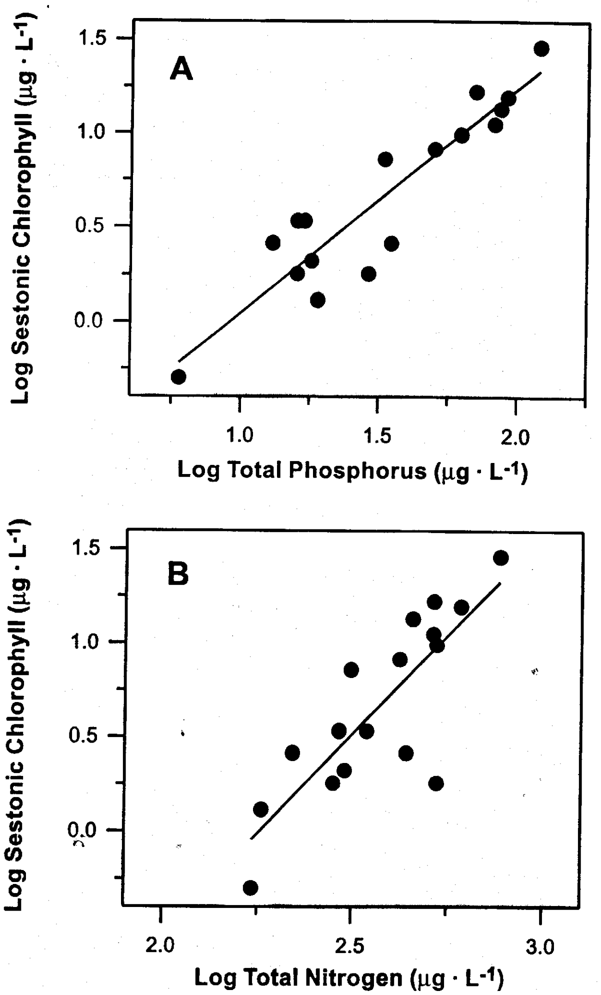
to sestonic Chl were the result of streams receiving municipal sewage treatment effluent and draining urban land uses. One stream (Blythes Creek) was sampled at 2 and 13 km below a sewage treatment outfall (urban land use composed 25.2 and 7.2% of catchment area); a second stream (Straight Fork) was sampled at 3, 9, and 20 km below an outfall (urban land use composed 12.7, 6.5, and 5.2% of catchment area). Along both streams, TP and TN levels declined by some 90% between upstream and downstream sites. Sestonic Chl declined fourfold from upstream to downstream at these sites (Table 1).

Replacing the quadratic term with catchment area substantially improved the fit of both nutrient – sestonic Chl models:

$$\log \mathrm{Chl} = -1.52 + 0.71(\log \mathrm{TP}) + 0.51(\log \mathrm{area}) \quad (R^2 = 0.90,\ F = 91.0,\ p < 0.001,\ n = 23) \tag{3}$$

$$\log \mathrm{Chl} = -3.78 + 1.24(\log \mathrm{TN}) + 0.59(\log \mathrm{area}) \quad (R^2 = 0.84,\ F = 54.6,\ p < 0.001,\ n = 23). \tag{4}$$

Fig. 2. Relationship of sestonic Chl to (A) TP and (B) TN among sites on streams in the northern Ozarks, excluding sites influenced by nutrient additions from point sources.



Nonpoint source sites

When the sestonic Chl analysis was limited to the 17 sites that were unaffected by point source nutrient additions, there was a strong linear relationship with both TP and TN, and in neither case was the relationship improved by the addition of a quadratic term (Fig. 2):

$$\log \mathrm{Chl} = -1.15 + 1.20(\log \mathrm{TP}) \quad (R^2 = 0.85,\ F = 90.4,\ p < 0.001,\ n = 17) \tag{5}$$

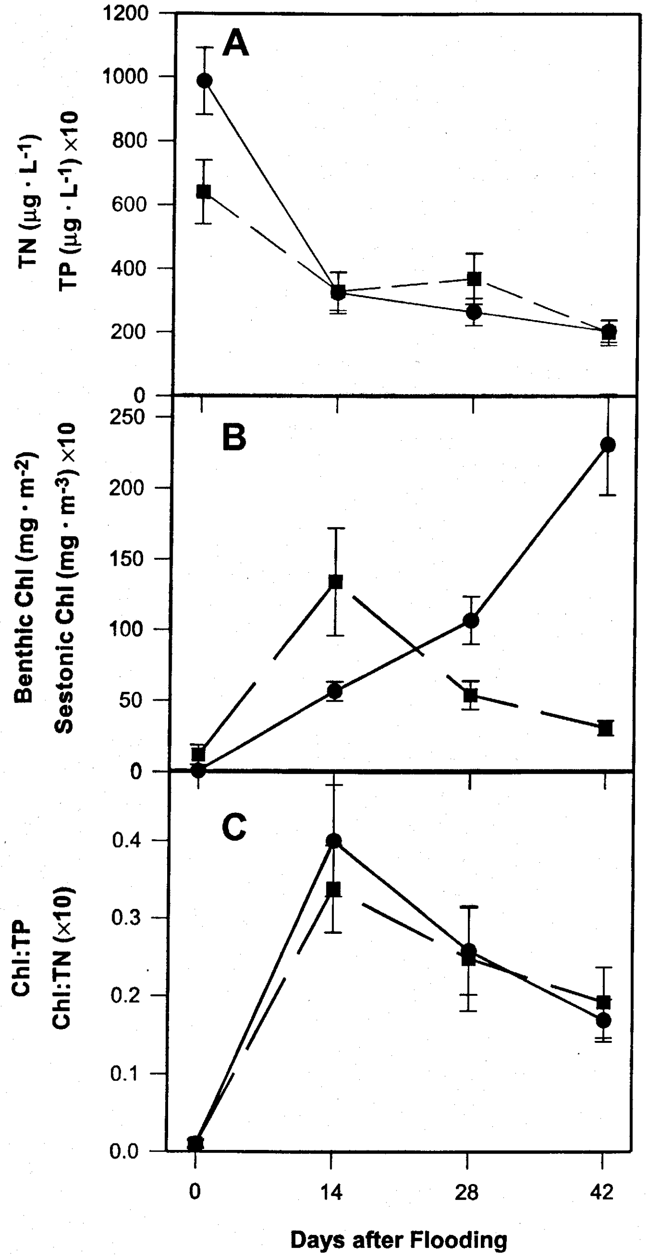
$$\log \mathrm{Chl} = -4.83 + 2.14(\log \mathrm{TN}) \quad (R^2 = 0.65,\ F = 30.8,\ p < 0.001,\ n = 17). \tag{6}$$

Adding catchment area to the linear nutrient–Chl relationships (Fig. 2) resulted in the following:

$$\log \mathrm{Chl} = -1.53 + 0.98(\log \mathrm{TP}) + 0.33(\log \mathrm{area}) \quad (R^2 = 0.94,\ F = 111.9,\ p < 0.001,\ n = 17) \tag{7}$$

$$\log \mathrm{Chl} = -4.53 + 1.65(\log \mathrm{TN}) + 0.45(\log \mathrm{area}) \quad (R^2 = 0.84,\ F = 36.5,\ p < 0.001,\ n = 17). \tag{8}$$

Fig. 3. Temporal variation in (A) TN (circles) and TP (squares), (B) benthic Chl (circles) and sestonic Chl (squares), and (C) ratios of sestonic Chl to TN (circles) and TP (squares) following catastrophic flooding in the northern Ozarks. Values represent the mean and SE of 17 sites.



Nutrient concentrations are strongly associated with land cover among nonpoint source streams in the Ozark Plateau (Smart et al. 1985; Perkins et al. 1998). Because of this, we were able to model sestonic Chl in the nonpoint source streams reasonably well by using the proportion of the catchment composed of either forest (negative relationship) or row crop agriculture (positive relationship) along with catchment area:

$$\text{(9)}\quad \log \text{Chl} = 0.30 - 1.40(\%\ \text{forest}) + 0.52(\log \text{area})$$
$$(R^2 = 0.90,\ F = 62.5,\ p < 0.001,\ n = 17)$$

Table 2. Mean, SD, and range of average TN, TP, sestonic Chl, and benthic Chl for streams sites not affected by point source effluent (n = 17).

Variable	Mean	SD	Range
TN (µg·L^{-1})	404	161	172–765
TP (µg·L^{-1})	45	34	6–119
Sestonic Chl (µg·L^{-1})	7.7	7.6	0.5–29.0
Benthic Chl (mg·m^{-2})	49.6	16.1	15.2–79.2
Sestonic Chl:TN	0.016	0.011	0.003–0.038
Sestonic Chl:TP	0.154	0.060	0.062–0.244

$$\text{(10)}\quad \log \text{Chl} = -0.85 + 2.18(\%\ \text{row crop}) + 0.56(\log \text{area})$$
$$(R^2 = 0.82,\ F = 32.0,\ p < 0.001,\ n = 17).$$

Conditions after a catastrophic flood

Following the flood, TP concentrations among the nonpoint source streams averaged some 50% greater than the overall mean, and after 42 days, values had declined to about half the long-term average (Fig. 3; Table 2). Over the same period, TN dropped from double to about half of the overall mean (Fig. 3; Table 2). Sestonic Chl was <2 µg·L^{-1} at all but two sites after the flood but peaked at approximately twice the overall mean at 14 days and declined thereafter (Fig. 3; Table 2). Depicted as Chl:TP and Chl:TN, the response of sestonic Chl to nutrients was quite dramatic at 14 and 28 days (Fig. 3). After 42 days, sestonic Chl, Chl:TP, and Chl:TP remained elevated at a few sites, but at most sites were typical of the overall average.

An analysis of nutrient–Chl relationships as modified by catchment area on each of the postflood sampling dates showed that on any given date, either TP or TN and catchment area could account for 55–74% of the variance in log Chl. Thus, while accounting for a smaller proportion of the variation than was the case for averaged data (eqs. 7 and 8), the functional relationships between algae and nutrients as modified by catchment area still apply. Using the empirical equations for Chl generated from mean values of these variables from the nonpoint source sites (eqs. 7 and 8), we found that the model overestimated conditions immediately after the flood (day 0), underestimated Chl at days 14 and 28, and most accurately predicted Chl at 42 days after the flood (Figs. 4 and 5).

Although we found significant relationships between overall mean values of sestonic Chl and TP and TN, and previous work has found similar associations between benthic Chl and nutrients (Lohman et al. 1992), we found no correlation between benthic and sestonic Chl (Fig. 6). The absence of a strong correlation between the two is also apparent in the postflood recovery patterns in which sestonic Chl peaks after 14 days whereas benthic Chl continues to increase through day 42 (Fig. 3).

Discussion

There is a strong relationship between nutrients and sestonic Chl in northern Ozark streams. When considered over a broad range of nutrient conditions, the curvilinear relationship of log TP to log sestonic Chl suggests that sestonic algae will be most responsive to TP when concentration are

Fig. 4. Log–log plots of observed and predicted sestonic Chl from 17 sites 0, 14, 28, and 42 days after catastrophic flooding in fall 1986. Predicted values of sestonic Chl are calculated from eq. 7 based on TP and catchment area.

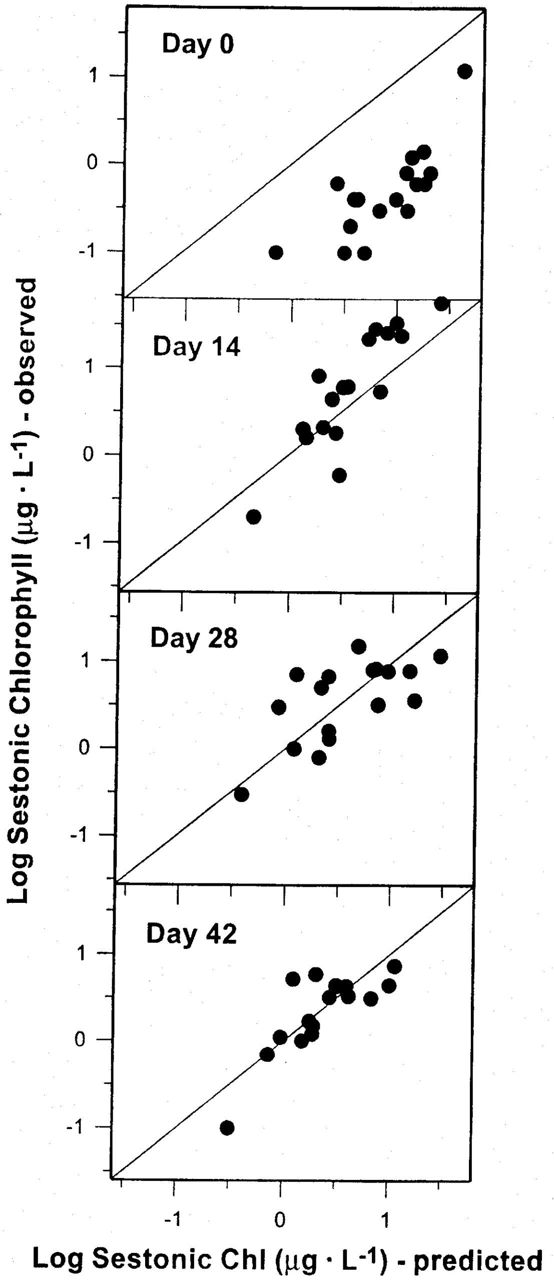
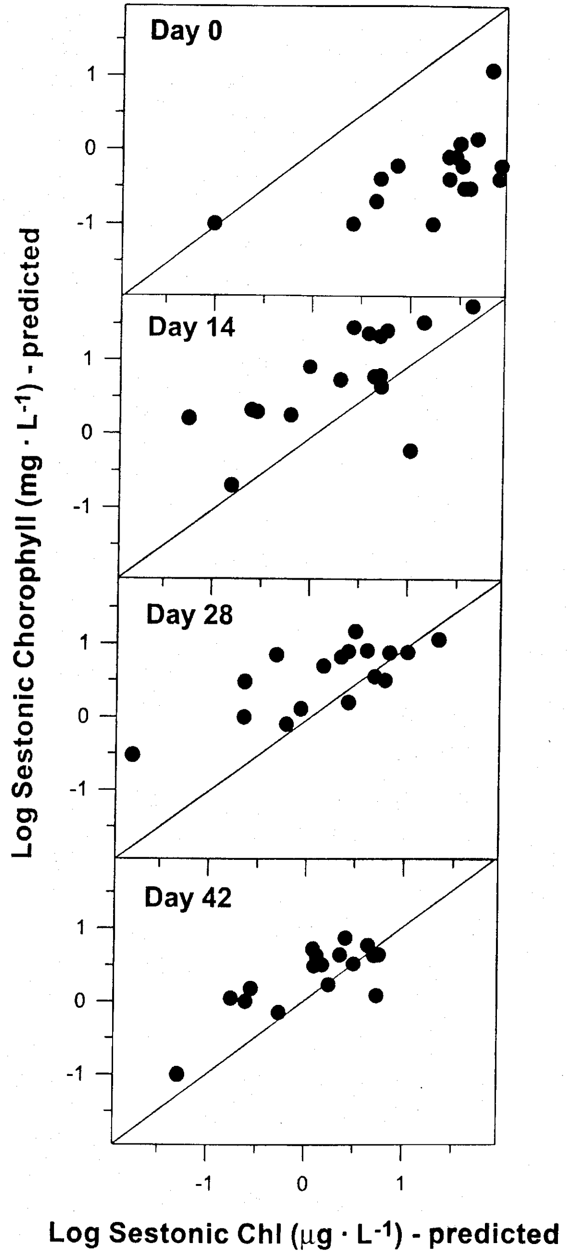


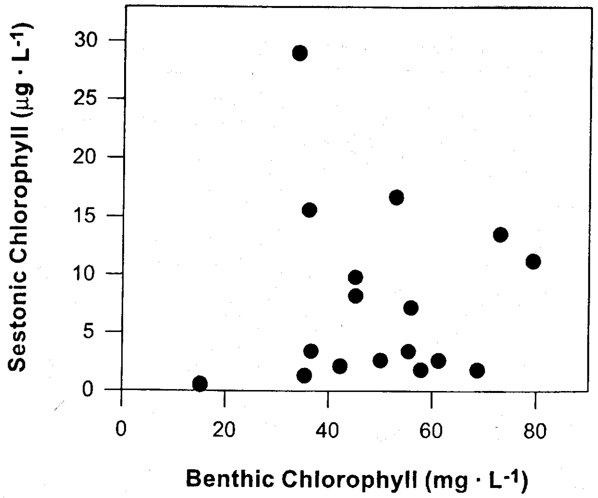
Fig. 5. Log–log plots of observed and predicted sestonic Chl from 17 sites 0, 14, 28, and 42 days after catastrophic flooding in fall 1986. Predicted values of sestonic Chl are calculated from eq. 8 based on TN and catchment area.



<100 $\mu g \cdot L^{-1}$. A linear model of log TP provided the best estimates of sestonic Chl when streams affected by sewage effluent were excluded, which also indicates the diminishing influence of P in highly enriched streams. Basu and Pick (1996) also found a linear relationship between Chl and TP among large rivers in eastern Canada. At TP concentrations of 100 $\mu g \cdot L^{-1}$, our quadratic and linear models would predict sestonic Chl in the range of 13–18 $\mu g \cdot L^{-1}$, roughly half of what might be expected in a lake of comparable nutrient status (McCauley et al. 1989). Sestonic Chl is generally lower in rivers than in lakes or reservoirs with similar nutrient conditions (Soballe and Kimmel 1987), and lower sestonic Chl concentrations can be expected in smaller streams than in large rivers (Van Nieuwenhuyse and Jones 1996).

Including catchment area substantially improved all TP – sestonic Chl models, including those that excluded high-nutrient sites affected by sewage effluent, as it did in the global model developed by Van Nieuwenhuyse and Jones (1996). Although nutrients are likely the primary determinant of sestonic Chl levels, physical conditions associated with catchment size are important secondary factors. The influence of hydraulic flushing rate and its consequent impact on algal washout have been identified by several authors (Kilkus et al. 1975; Soballe and Kimmel 1987; Van Nieuwenhuyse and Jones 1996). A decline in algal washout

Fig. 6. Relationship of sestonic Chl to benthic Chl among 17 sites on streams in the northern Ozarks of Missouri. Points represent the average values of samples collected bimonthly between March and November 1985 and 1986.



as catchment area increases may allow for more sestonic algal photosynthesis, as well as greater accumulation of dislodged benthic algae in the water column (Van Nieuwenhuyse and Jones 1996; Swanson and Bachmann 1976). Our results suggest that the effects of decreases in hydraulic flushing rate on sestonic algae may occur even over a small range of catchment area in this region. The streams in our study were all relatively small (second to fourth order) with catchment areas of 20.30–864.57 km^2. In contrast, Basu and Pick (1996) found that water residence time (a function of area) was not significant as a second variable in Chl–TP regressions among fifth-order and larger streams.

The success of the global model developed by Van Nieuwenhuyse and Jones (1996) in predicting sestonic Chl levels in northern Ozark streams suggests that it may be useful for estimating sestonic Chl in other regions as well. Unlike lakes, few models exist for predicting sestonic Chl levels in rivers (and, in particular, smaller streams), although a few models for predicting benthic algal biomass have been proposed (Biggs and Close 1989; Lohman et al. 1992; Dodds et al. 1997). We would point out that data from streams in this study were used in the construction of the Van Nieuwenhuyse and Jones (1996) model, but our sites made up <10% of the data in their global model. In addition, we used a single average value over 2 years for each site and expunged data collected during flood events whereas Van Nieuwenhuyse and Jones (1996) relied on seasonal averages (May–September) and calculated separate means for each year.

Our results also indicate that TN may be a good predictor of sestonic Chl in many regions. Although not considered in the global model of Van Nieuwenhuyse and Jones (1996), both quadratic and linear models using TN alone or TN and catchment area explained nearly as much variation in sestonic Chl (68–84%) as did TP-based models in northern Ozark streams. Given the prevalence of N limitation in many parts of midwestern and western North America (Grimm and Fisher 1986; Lohman et al. 1991, Lohman and Priscu 1992), N models may have particular efficacy for stream management. Land use, together with catchment size, was also a good predictor of sestonic Chl in northern Ozark streams without point source nutrient additions. As a consequence, it may be possible to estimate sestonic Chl in many streams where nutrient data are lacking if information on watershed land cover is available. This approach has been used successfully to predict Chl in lakes (Meeuwig and Peters 1996), and Biggs (1995) demonstrated the importance of agricultural land use in explaining among-site variation in benthic Chl in streams.

Nutrient–Chl models derived from long-term averages did reasonably well at predicting sestonic Chl in northern Ozark streams on individual sampling dates during the 42-day period following catastrophic flooding. That these models overestimated sestonic Chl immediately after the flood (day 0) is not surprising. If algal washout is a major determinant of sestonic biomass, then sestonic Chl in samples collected right after a high-water event should be substantially lower than just before the event whereas TN and TP are frequently elevated during such periods. Perhaps not coincidentally, the closest agreement between observed and predicted values of sestonic Chl occurred on day 42 when mean concentrations of both TP and TN were half of the overall mean values of the two nutrients.

Because both are influenced by nutrients, the absence of a correlation between benthic and sestonic Chl was somewhat surprising. This might be accounted for by differential effects of hydraulic flushing rates on benthic and suspended algae. Highly enriched but slow-moving streams might be expected to develop high levels of sestonic Chl but somewhat lesser accumulations of benthic Chl whereas enriched, fast-flowing streams may have greater benthic biomass and relatively low levels in suspension. Although a faster current velocity and a higher hydraulic flushing rate may reduce sestonic biomass, current velocity up to 50 cm·s^{-1} enhances nutrient uptake by benthic algae (Horner and Welch 1981). At low current velocities, high levels of suspended algae may also reduce light penetration and thereby limit the growth of benthic algae. Consequently, the greatest benthic algal production seems likely to occur at intermediate flow rates (Stevenson 1996).

Our results demonstrate that sestonic Chl is closely associated with both TP and TN in Ozark streams. Those relationships are affected by catchment size, presumably as it affects flow regimes and water residence times within streams. The global model developed by Van Nieuwenhuyse and Jones (1996) accurately predicted sestonic Chl levels in relationship to TP in our streams at several temporal scales and indicates that nutrient – sestonic Chl models may have broad application in running-water systems.

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