An Optics Model for Onondaga Lake[1]

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ABSTRACT

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A deterministic optics model for predicting measures of light penetration, including Secchi disc transparency (or clarity; SD) and the vertical attenuation coefficient for downward irradiance (K_d), from concentrations of various attenuating substances, is developed, calibrated, and applied for culturally eutrophic Onondaga Lake, NY. The model is an invaluable management tool for establishing the appropriate focus and realistic expectations for improving clarity in the lake. The model is consistent with optical theory, partitioning attenuation according to the processes of absorption and scattering, and materials contributing to these processes. The model is developed from optical measurements made for the lake over the 1987-1990 interval, reported by Perkins and Effler (1996), and attendant estimates of the values of absorption and scattering coefficients presented herein. It is demonstrated that the primary components responsible for low SD and high K_d in the lake are phytoplankton and tripton (other than $CaCO_3$ particles). Gelbstoff and $CaCO_3$ particles are relatively unimportant. Management efforts to improve clarity should focus on the lake's cultural eutrophication problem. Terrigenous particle inputs received during runoff events would continue to substantially reduce clarity for brief periods if they are not abated.

Key Words: clarity, light attenuation coefficient, Secchi disc, absorption, scattering, optics, model, cultural eutrophication.

Clarity is a primary feature of water quality. Indeed, major improvements in clarity are often expected from restoration programs for culturally eutrophic lakes. Implicit in this expectation is that phytoplankton biomass is the dominant light attenuating component. Though that is often the case, it is not always an appropriate assumption. Other materials can play an important, and even dominant, role in regulating clarity (i.e., light penetration). These include dissolved yellow substances (gelbstoff; Kirk 1976), mineral particles produced internally (particularly $CaCO_3$; Effler et al. 1987, 1991, Weidemann et al. 1985), and particles supplied as terrigenous inputs (Kirk 1985). If non-phytoplankton constituents regulate light penetration, a management program that is successful in reducing phytoplankton growth will achieve little in the way of increased clarity. In such cases, alternate management programs (e.g., erosion control in the watershed) may be more effective. Thus it can be extremely valuable to resolve the relative roles of various attenuating substances before restoration is attempted. A reliable "optical model" with this capability is an invaluable management tool to establish realistic expectations and to evaluate management alternatives and the feasibility of reaching goals for water clarity.

Here we develop a deterministic optics model for the two common measures of light penetration, Secchi disc transparency (clarity; SD, m) and the vertical attenuation coefficient for downward irradiance (K_d, 1/m). The model is developed and tested for culturally eutrophic Onondaga Lake, NY. The model is then used to partition the relative contributions of different attenuating materials and establish an appropriate management approach to achieve improved clarity. Model development relies on measurements of apparent optical properties and attenuating components presented in the companion paper (Perkins and Effler 1996).

Both empirical and deterministic models have been developed to quantify the dependence of K_d, and SD, on the concentration(s) of light attenuating materials. Most of the empirical models are simple linear relationships between K_d, or 1/SD, and phytoplankton biomass, as measured by chlorophyll (e.g., Megard et al. 1979, Tilzer 1983). The optics of many lakes cannot be modeled accurately with simple empirical expressions because of uncoupled (e.g., independent and uncorrelated) variations in attenuating components, or omission of an important constituent. Deterministic optical models cover a range of complexity. They all necessarily quantify the relative contributions of the absorption and scattering processes, as specified by the magnitude of the coefficients a (1/m) and b(1/m), respectively. The contribution of various attenuating components to a and b can be determined analytically through a program of appropriate field optical measurements (see Perkins and Effler 1996) and paired laboratory analyses (e.g.,

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Weidemann and Bannister 1986). A necessary first step for a deterministic modeling approach is the estimation of *a* and *b*. Thus, as part of the overall model development, we present estimates of *a* and *b* for the lake, and partition these coefficients according to contributions of the various attenuating components.

Methods

Study System

Background information related to the degraded optical features of Onondaga Lake and a description of the optics monitoring program were presented in the companion paper (Perkins and Effler 1996). Distributions of measurements of attenuating materials and apparent optical properties reported by Perkins and Effler (1996), upon which this analysis depends, are presented here again for completeness (Fig. 1). Estimates of *a* and *b* are presented for the 1985-1990 interval; the period for which the necessary optics measurement program (Perkins and Effler 1996) was conducted. The model is based on the program conducted over the 1987-1990 interval, for which the most complete optical information exists (Perkins and Effler 1996). The distributions of the optical parameters are partitioned into two groups, demarcated by the closure of the soda ash/chlor-alkali manufacturer in 1986. The representation of "before" and "after" conditions in these distributions is uneven (e.g., population sizes are not equal) because of changes in the optics monitoring program (Perkins and Effler 1996) over its tenure. Shifts in certain of the parameters following closure, particularly to increased light penetration, were attributed largely to reductions in the concentration of chlorophyll (C_T; mg/m^3) and turbidity (Perkins and Effler 1996), probably caused by increased zooplankton grazing (Siegfried et al. 1996). Substantial short-term variations in the spectral features of downwelling attenuation occur, associated with the strong dynamics in phytoplankton biomass commonly observed in the lake (Perkins and Effler 1996).

Estimation and Partitioning of a and b

The value of *a* for the photosynthetically active radiation wavelength interval (PAR; 400-700 nm) at the 10% light depth ($z_{0.1}$, m) was calculated according to the Gershun-Jerlov equation (Jerlov 1976)

$$a = \bar{\mu} \cdot K_E \qquad (1)$$

where $\bar{\mu}$ = average cosine, at $z_{0.1}$, and K_E = the attenuation coefficient for net downwelling irradiance (E_d-E_u; E_d = downwelling irradiance, and E_u = upwelling irradiance at $z_{0.1}$ (µE/m^2/s)). Perkins and Effler (1996) reported that K_E was essentially equivalent to the attenuation coefficient for downwelling irradiance at $z_{0.1}$, K_d, in Onondaga Lake. Kirk's (1981b) functions were used to obtain the ratio b/a and $\bar{\mu}$ from the measured reflectance, R (= E_u/E_d), at $z_{0.1}$. The value of *b* for PAR at $z_{0.1}$ is then calculated by

$$b = a \cdot (b/a) \qquad (2)$$

Spectral average absorption coefficients for PAR for water (a_w, 1/m) and for gelbstoff (a_y, 1/m) were determined from the respective absorption spectra and spectral downwelling irradiance ($E_{d(\lambda)}$) data from $z_{0.1}$, according to (Weidemann and Bannister 1986)

$$a_x = \frac{\int_{400}^{700} E_{d(\lambda)} a_{x(\lambda)} d\lambda}{\int_{400}^{700} E_{d(\lambda)} d\lambda} \qquad (3)$$

where a_x = spectral average absorption coefficient for component x (= w, and y; 1/m). This equation weighs the spectral absorption coefficient according to the irradiance spectrum at $z_{0.1}$ to obtain values of a_x that can be directly compared to *a* for PAR determined at $z_{0.1}$. The absorption by water, $a_{w(\lambda)}$, is known (Smith and Baker 1981). The absorption by gelbstoff, $a_{y(\lambda)}$, is derived from absorbance spectra measured on filtered samples, as reported by Perkins and Effler (1996). The mean spectral absorption coefficient for particles (a_p, 1/m; e.g., phytoplankton and tripton) was determined by difference

$$a_p = a - (a_w + a_y) \qquad (4)$$

This is less desirable than estimating a_p directly from laboratory measurements (e.g., Kirk 1980, Weidemann and Bannister 1986). However, this approach is supported by the findings of Weidemann and Bannister (1986); they observed good agreement (e.g., most within 10%) between *a* and the summation of the independently determined spectral average values of a_w, a_y, and a_p in Irondequoit Bay, NY.

In hardwater lakes *b* has been partitioned according to:

$$b = b_{nc} + b_c \qquad (5)$$

where b_{nc} = spectral average scattering coefficient for non-calcite particles (i.e., phytoplankton and tripton other than calcite particles; 1/m), and b_c = spectral average scattering coefficient for calcite ($CaCO_3$) particles (1/m; Effler et al. 1987, 1991, Weidemann et al. 1985). This partitioning is supported by the turbidity measurements reported by Perkins and Effler (1996);

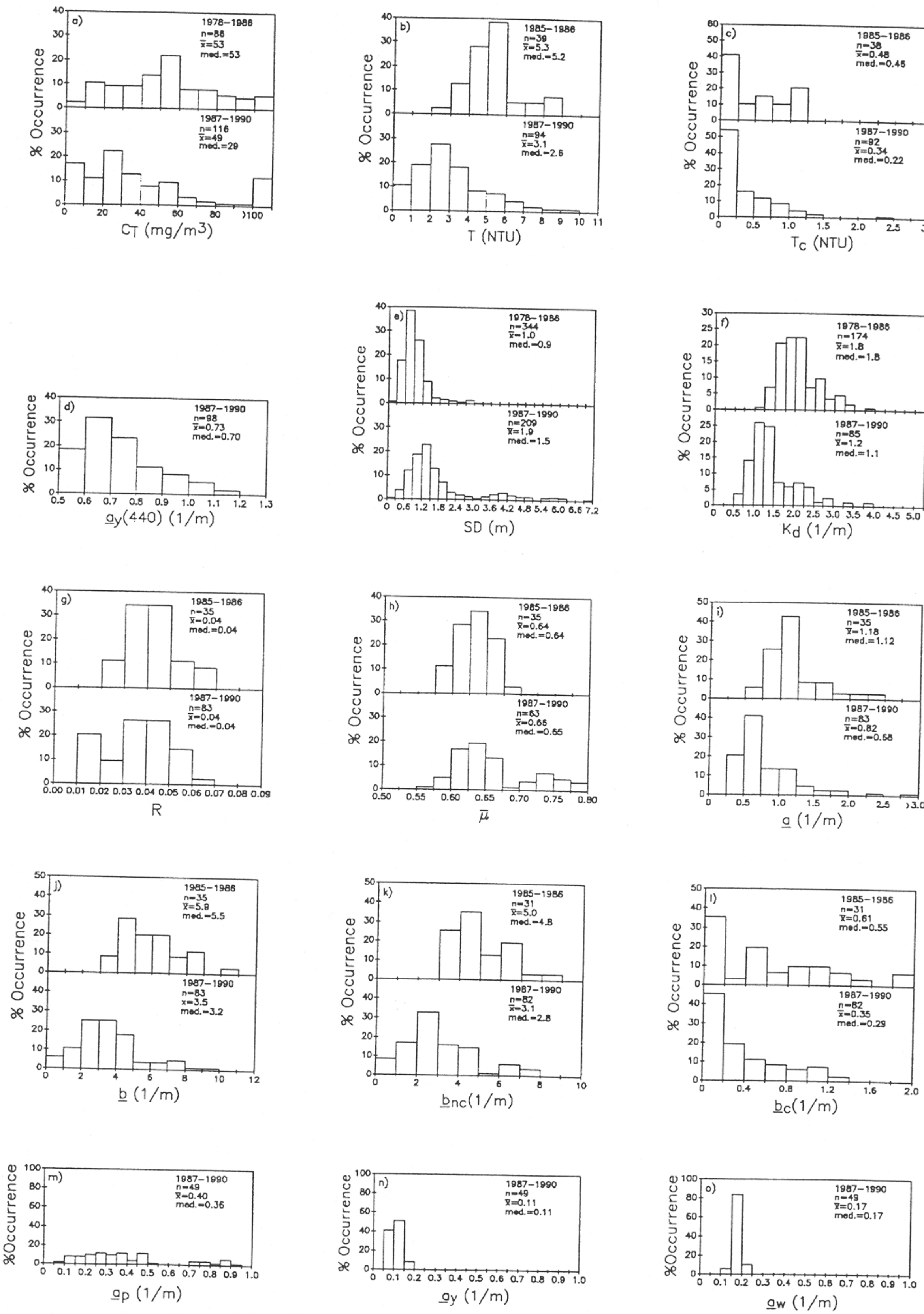

Figure 1.–Populations of measurements of attenuating materials, apparent optical properties, and estimates of *a*, *b*, and their components, in Onondaga Lake, for two periods: a) C_T, b) T, c) T_c, d) $a_{y(440)}$, e) SD, f) K_d, g) R, h) $\bar{\mu}$ (from Kirk (1981b) function), i) *a*, j) *b*, k) b_{nc}, l) b_c, m) a_p, n) a_y, and o) a_w. Parts a) through g) are from Perkins and Effler (1996).

b_c is calculated according to:

$$b_c = (T_c/T) \cdot b \tag{6}$$

where T = turbidity (NTU), and T_c = turbidity associated with calcite (NTU), and b_{nc} is calculated by difference (see Equation (5); Effler et al. 1991).

Distributions of *a*, *b*, and Components

The estimates and the partitioning of *a* and *b* can be checked in two ways. First, the estimates of *b* were similar to the measured (Perkins and Effler 1996) values of T. The relationship between *b* and T has been described by:

$$T = \alpha \cdot b \tag{7}$$

where α is a constant (NTU · m; Effler 1988, Weidemann and Bannister 1986). The value of α has been observed to fall in the narrow range of about 0.8 - 1.25 NTU · m (DiToro 1978, Effler 1988, Effler et al. 1991, Kirk 1981a, Weidemann and Bannister 1986). The average value of α for 118 paired measurements of T and estimates of *b* for Onondaga Lake over the 1985-1990 period was 0.84 (± 0.29). Secondly, determinations of $\bar{\mu}$ from measurements (Perkins and Effler 1996) compared reasonably well with estimates from Kirk's (1981b) functions (the basis for estimating *a* adopted here). Recall that $\bar{\mu}$ is linearly coupled to the estimate of *a*, according to Equation (1). The percent difference in the two values of $\bar{\mu}$ was < 20% for 60 of 61 paired estimates over the 1987 - 1990 interval. Most of the differences can be attributed to limitations in the measurements, including imperfect configuration of the (3) sensors (Perkins and Effler 1996).

The strong dynamics in attenuating materials and apparent (measured) optical properties in Onondaga Lake were illustrated for 1988 by Perkins and Effler (1996). These conditions are presented here again (Fig. 2 (a-f)), for reference and to evaluate the coupled estimates of *a* and *b* and their components (Fig. 2h and i). The distribution of $\bar{\mu}$ (Fig. 2g) is based on the Kirk (1981b) function. The major features of the temporal structure reflect the dynamics of phytoplankton biomass (Fig. 2a) and the timing and magnitude of external inputs of tripton associated with major runoff events (see arrows of Fig. 2b, and further discussion of Perkins and Effler (1996)). Well-defined peaks in *a* and *b* track the peaks in attenuating materials. Inflections in *a* and *b* generally coincide, indicating the dynamics of *a* and *b* are largely regulated by particles that both absorb and scatter light. The disparity in the relative response of

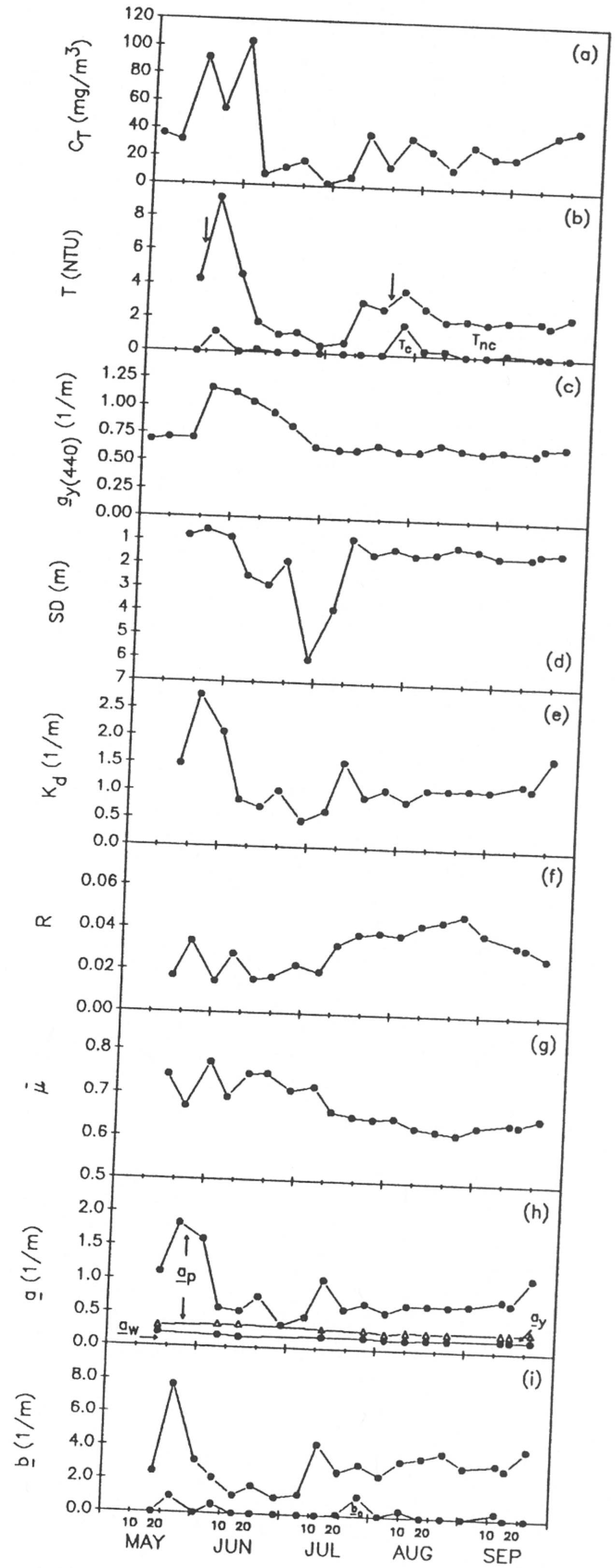

Figure 2.–Temporal trends in attenuating materials, apparent optical properties, and estimates of *a*, *b*, and their components, in Onondaga Lake, for 1988: a) C_T, b) T and T_c (arrows indicate occurrence of major runoff events), c) $a_{y(440)}$, d) SD, e) K_d, f) R, g) $\bar{\mu}$, h) a, a_w, a_y, and a_p, and i) b and b_c. Portions [a) - f)] from Perkins and Effler (1996).

these inherent optical properties provides some insight into the optical characteristics of the attenuating materials. The much greater response of b than a to the May storm indicates the terrigenous particles absorbed relatively less light than the phytoplankton. Note that the reduction in a was modest one week after the runoff event (Fig. 2h), because of the increase in C_T (Fig. 2a), but that a major decrease in b was observed (Fig. 2i). Dynamics in a_p, associated with phytoplankton and tripton, were responsible for the temporal structure in a observed in the lake, as the components of a_w and a_y remained relatively uniform (Fig. 2h). Except during the clearing event of late June (Figs. 2d and e), a_p was the largest component of a. The average contributions of a_p, a_w, and a_y to a over the May-September interval of 1988 were 59, 24, and 17% respectively, similar to that observed in the other years of the 1987-1990 interval. Variations in a_p appear to have generally tracked those of C_T and T. The $CaCO_3$ (b_c) contribution to b in 1988 was significant only after the two runoff events. Johnson et al. (1991) have attributed the enhanced precipitation of $CaCO_3$ in the lake following runoff events to the influx of terrigenous particles that serve as nucleation sites.

The distributions of estimates of $\bar{\mu}$, a, b, and components of a and b, have been added to the distributions of measurements of attenuating materials and optical properties reported by Perkins and Effler (1996; Fig. 1). The distributions of $\bar{\mu}$ (Fig. 1h) are consistent with those documented for R (Fig. 1g). The occurrence of distinctly higher $\bar{\mu}$ observations following closure of the facility reflects very low particle concentrations during the clearing events. This is manifested as a decrease in the relative contribution of scattering to attenuation. Downward shifts in both a (Fig. 1i) and b (Fig. 1j) since closure of the soda ash/chlor-alkali facility are responsible for the observed increase in light penetration (Fig. 1e and f). The decrease in the minimum value of b is particularly striking. It reflects the occurrence of lower particle concentrations, and is probably a manifestation of non-selective feeding behavior by daphnids. The shift to lower b_c values (Fig. 1l) following closure is also consistent with the reported reduction in $CaCO_3$ deposition rate (Driscoll et al. 1994, Womble et al. 1996). In general, b_{nc} (Fig. 1k) has been the dominant component of b. Estimates of the components of a are available only for the interval following closure. The distribution for a_p (Fig. 1m) is quite broad, consistent with the observed wide variations in phytoplankton biomass. Variations in a_y reflect the influence of modest variations in gelbstoff concentration (Perkins and Effler 1996) and changes in the spectral quality of penetrating irradiance associated with the dynamics of phytoplankton biomass (see later discussion). The minor variations in a_w are a result only of changes in spectral quality (Weidemann and Bannister 1986).

Optics Model for Onondaga Lake

Optics Framework

The model is deterministic (mechanistic) in that it adopts widely accepted expressions relating K_d and SD to a and b that are consistent with theory, though it incorporates empirical relationships to support certain features of the partitioning of a and b. The value of K_d can be calculated from the spectral average values of a and b, and the angle of incidence of photons at the surface (i.e., time of day), according to the following expression developed by Kirk (1981a, 1984), based on Monte-Carlo analyses of the underwater light field

$$K_d = (a^2 + 0.256\, a\, b)^{0.5} \tag{8}$$

Based on contrast transmittance theory, it has been demonstrated that SD is inversely proportional to the sum of K_d and the beam attenuation coefficient, c (= $a + b$; 1/m) (Priesendorfer 1986, Tyler 1968):

$$SD = \frac{N}{K_d + c} \tag{9}$$

where N = constant (dimensionless). Different values of N have been published (e.g., Holmes 1970, Tyler 1968), and the value of N is now understood to vary in response to uncontrollable conditions (e.g., wave action, cloud cover) that prevail during field measurements. Priesendorfer (1986) has described N as a quasi-constant, and gives the typical range of N to be 8.0 to 9.6.

The contrast transmittance theory has been applied to the 1985-1990 data set (Fig. 3). Linear least square regression fits are presented for the total population and for a commonly observed subset of conditions (SD $\leq$3.0 m and $(K_d + c)^{-1} \leq 0.4$ m). The slopes are estimates of N (Equation (9)). The values determined for Onondaga Lake (7.9 and 7.1 for all observations and the subset of commonly observed values, respectively) fall slightly below the range identified by Priesendorfer (1986). Some scatter is observed (Fig. 3); particularly for clearing events. We attribute this to variations in the conditions under which measurements were made and imperfections in the measurements themselves. However, the linearity observed for the commonly observed range of inherent and apparent optical properties supports the contrast transmittance theory

(Equation (9)). The relationship(s) presented for Onondaga Lake (Fig.3) represents a mechanistically sound, and reliable, basis to project the implications of changes in a and b, mediated by changes in the concentrations of attenuating substances, on the clarity of Onondaga Lake.

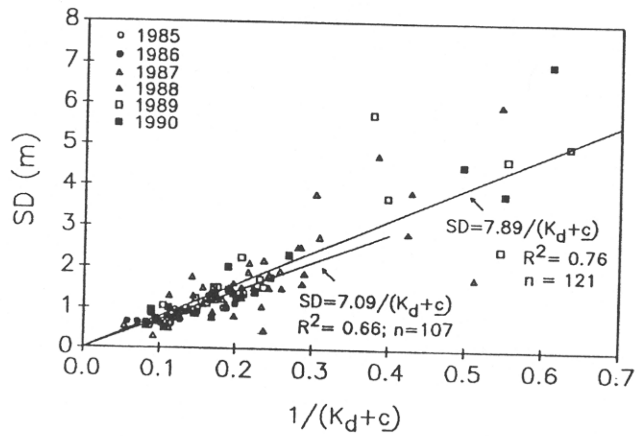

Figure 3.–Application of the contrast transmittance theory for SD in Onondaga Lake, based on the 1985-1990 data set. Slope is equal to N (Equation (9)).

Attenuating Materials, Absorption and Scattering Components

Relationships between attenuating materials and absorption and scattering components are established here that couple the constituent concentrations to measures of light penetration through Equations (8) and (9). The dependencies of a_p, a_w, a_y, and b_{nc} on C_T are evaluated here from the 1987-1990 data base (Fig. 4(a-d)). Variations in C_T explained 65% of the observed variability in a_p (Fig. 4a). We attribute the observed scatter in this relationship primarily to variable contributions of tripton (e.g., runoff events; Perkins and Effler 1996), but also to differences in absorption characteristics and chlorophyll content of phytoplankton (Kirk 1983). The a_p component can be partitioned between phytoplankton and tripton, according to

$$a_p = a_p' + K_a \cdot C_T \qquad (10)$$

where a_p' = spectral average absorption coefficient for tripton (1/m), and K_a = chlorophyll-specific absorption coefficient (m²/mg chlorophyll). According to linear least square regression analysis (Fig. 4a), the best estimate of K_a for Onondaga Lake is 0.0084 m²/mg chlorophyll, which falls well within the range of values reported in the literature (e.g., Bannister and Weidemann 1984). The distinctly non-zero intercept represents an "average" absorption by tripton (a_p' = 0.132/m). This component is subject to wide variations. For example, it is much greater following major runoff events, and becomes substantially smaller during clearing events (e.g., Fig. 2h).

Shifts in spectral quality associated with the dynamics of absorbing particles, particularly phytoplankton, as documented by Perkins and Effler (1996), cause variations in both a_w and a_y. The character of these interactions can be viewed as a form of feedback

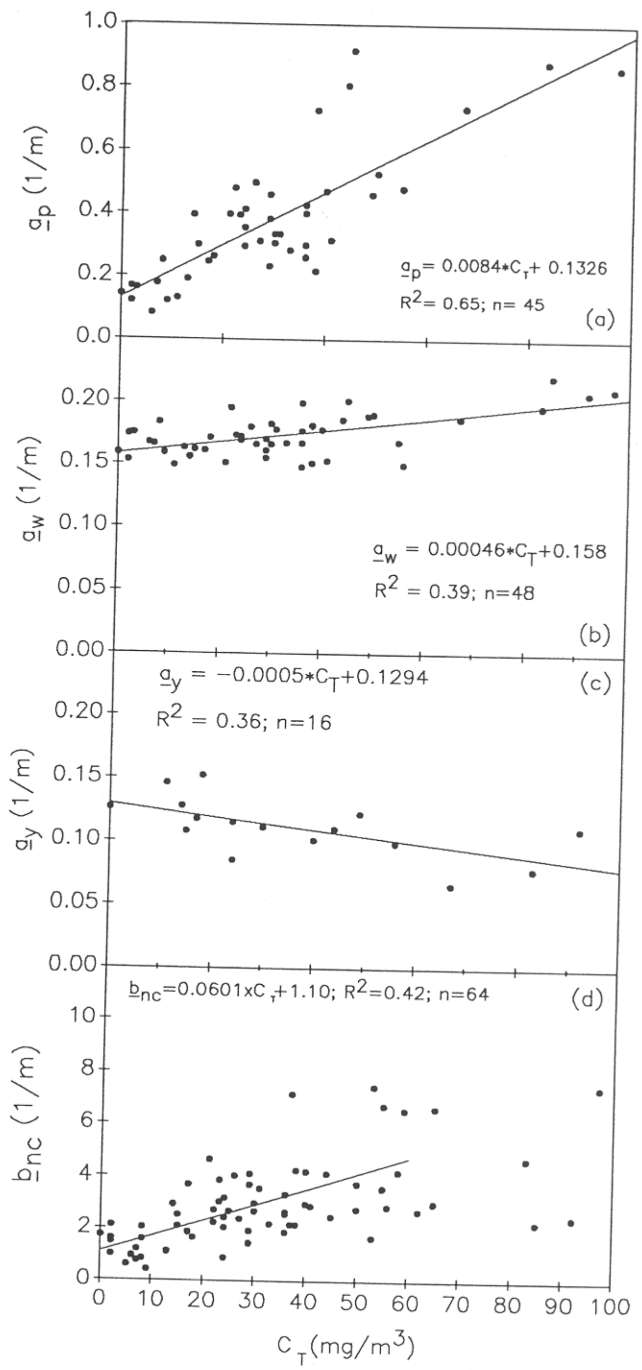

Figure 4.–Evaluation of the dependencies of attenuating components on the concentrations of C_T in Onondaga Lake, for the 1987-1990 data base: a) a_p, b) a_w, c) a_y, and d) b_{nc}.

from phytoplankton pigments (Fig. 4b and c), which is consistent with optical theory (Kirk 1983). The value of a_w increased as C_T increased (Fig. 4b), because absorption by phytoplankton pigments tends to shift the distribution of penetrating irradiance to the higher wavelengths which are preferentially absorbed by water itself. Feedback from chlorophyll concentrations has the opposite effect on a_y, which tends to decrease at higher C_T concentrations (Fig. 4c), because the preferential absorption of blue light by phytoplankton pigments leaves less light available for absorption by gelbstoff, which also preferentially absorbs at these lower wavelengths. The analysis of Fig. 4c considers only a subset (n = 16) of the gelbstoff observations corresponding to a narrow range of $a_{y(440)}$ ($0.65/m \leq a_{y(440)} \leq 0.80/m$) to isolate the phytoplankton feedback effect from that of variations in gelbstoff concentration. These feedback effects of C_T concentrations are not numerically important to the model of light penetration for the lake; the effects on a_w and a_y are compensating (Fig. 4b and c), and small compared to the magnitude of a (Fig 2h)). However, they have been accommodated in the model to make it more mechanistically complete.

The relationship between b_{nc} and C_T is highly variable (Fig. 4d). Factors contributing to the high variability include uncoupled (i.e., independent and uncorrelated to variations in phytoplankton biomass) variations in tripton, the disparate species-specific scattering properties of phytoplankton (Bricaud et al. 1983), and differences in the cellular content of chlorophyll. The value of b_{nc} can be partitioned between phytoplankton and tripton (other than $CaCO_3$), according to

$$b_{nc} = b' + K_b \cdot C_T \qquad (11)$$

where b' = spectral average scattering coefficient for tripton other than $CaCO_3$ (1/m), and K_b = chlorophyll-specific scattering coefficient (m^2/mg chlorophyll). A high degree of variability has been observed elsewhere, e.g., Weidemann and Bannister (1986) found that 45 of 55 (82%) observations fell in the envelope formed by K_b values of 0.05 and 0.15 m^2/mg chlorophyll. The estimates of K_b and b' for Onondaga Lake, based on the linear least squares regression analysis (Fig. 4d), are 0.06 m^2/mg chlorophyll and 1.1/m, respectively. The fraction of the Onondaga Lake population (Fig. 4d) bounded by the envelope formed by K_b values of 0.05 and 0.15 m^2/mg chlorophyll is very sensitive to the value of b', which undoubtedly varies; for b' = 1.1/m, about 60% of the observations were bounded.

The spectral average value of a_y increases as gelbstoff levels increase. This relationship is quantified for Onondaga Lake by linear least squares regression analysis of the paired estimates of a_y and measurements of $a_{y(440)}$ (Fig. 5). Finally, the values of b_c = 0.4/m (Fig. 11) and N = 7.89 (Fig. 3) were adopted to complete the specification of necessary model inputs.

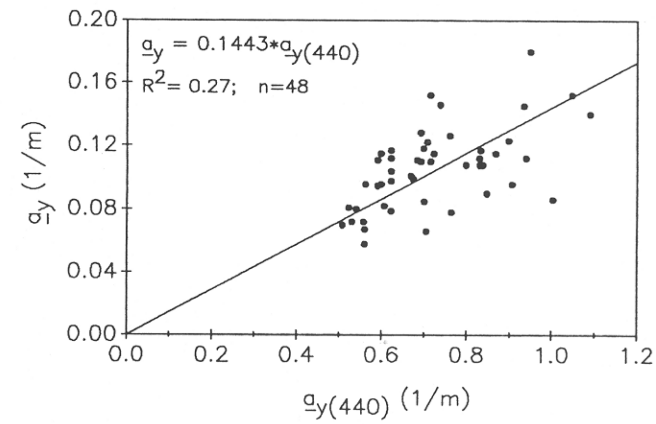

Figure 5.–Evaluation of the dependency of a_y on gelbstoff concentration (as $a_{y(440)}$).

Model Performance, Sensitivity, Scenarios and Management Implications

The predicted K_d-C_T and SD-C_T relationships obtained by application of the model (i.e., optical framework of Equations (8) and (9), and linear least square regression relationships presented in Figs. 4 and 5) compare well to the observations for the 1987-1990 data base (Fig. 6a and b). Thus the model can be described as calibrated.

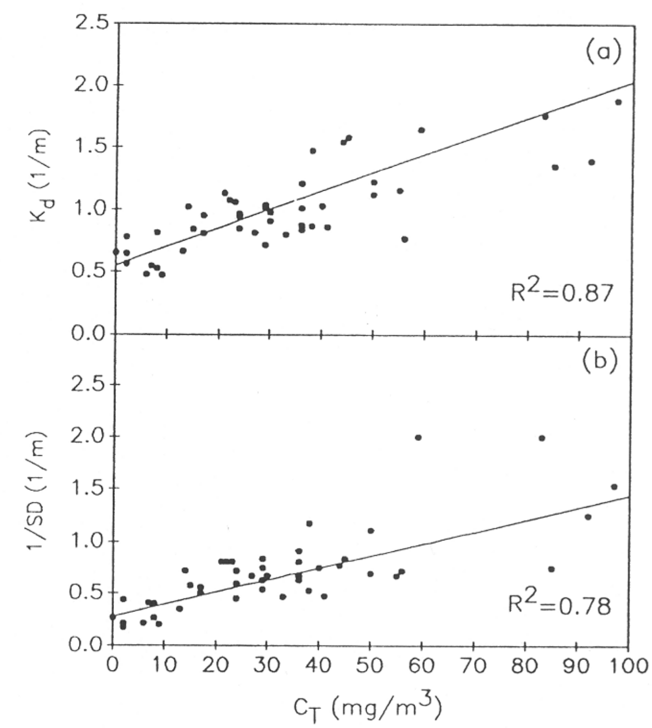

Figure 6.–Performance of Onondaga Lake optics model in matching observations for 1987-1990: a) K_d, and b) 1/SD.

Sensitivity analyses were conducted to evaluate the relative importance of sources of variability (e.g., Figs. 4 and 5) to the overall variability in the K_d-C_T and SD-C_T relationships (Fig. 6). Uncertainty limits were set according to statistical measures of performance of the contributing component relationships. This maintains a degree of objectivity in the sensitivity analyses. The uncertainty limits for sensitivity analyses on the a_p-C_T and b_{nc}-C_T relationships were selected as ± 1 standard error of estimate on the y - intercept (a_p' and b', respectively). The uncertainty limits for N were set as ± 1 standard error of the best estimate of N. The K_d-C_T part of the model is much more sensitive to the uncertainty in the a_p-C_T relationship than the SD-C_T predictions (Fig. 7a and b). Conversely, the SD-C_T part of the model is much more sensitive to the uncertainty in the b_{nc}-C_T relationship (Fig. 7c and d). The model is relatively insensitive to other estimates (e.g., N, Fig. 7e) and relationships (e.g, a_w-C_T and a_y-C_T) incorporated in the model. These analyses indicate that the major sources of variability in the K_d-C_T and SD-C_T relationships in Onondaga Lake are variations in the a_p-C_T and b_{nc}-C_T relationships, respectively. Much of this is probably due to the dynamics of tripton in the lake.

The implications of changes in non-phytoplankton attenuating components on measures of light penetration can also be quantitatively evaluated with the model. As examples, model predictions of the relationships between K_d and gelbstoff concentration ($a_{y(440)}$) and SD and the tripton component of scattering ($b_c + b'$) for Onondaga Lake are presented (Fig. 8a and b), for two specified C_T concentrations. The specified C_T concentrations correspond approximately to annual minima and averages over the 1988 - 1990 interval. The SD - $a_{y(440)}$ and K_d - ($b_c + b'$) relationships are not shown, as these measures of light penetration are inherently less sensitive to these components (e.g, Fig. 7). Both of the modeled relationships are predicted to be linear

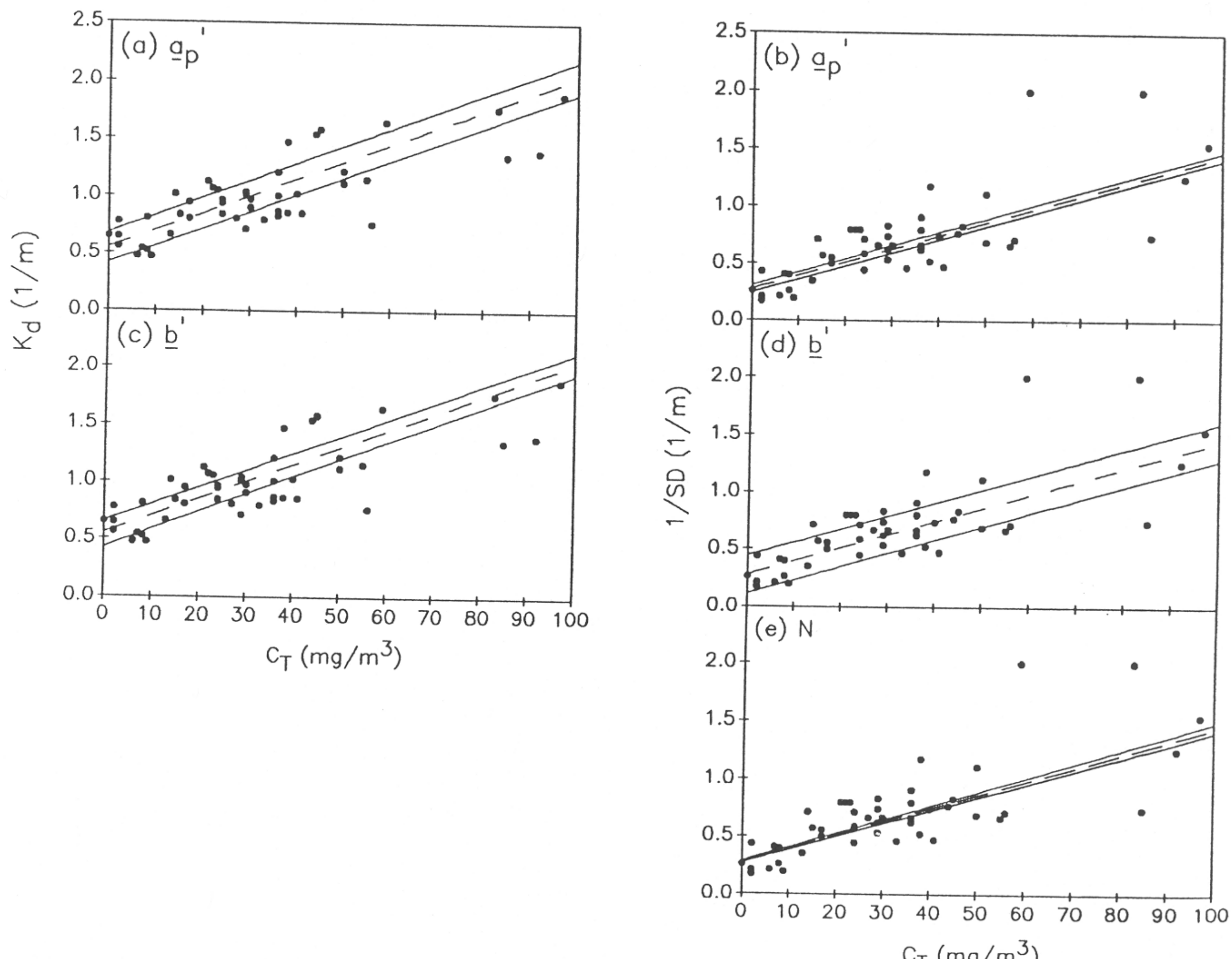

Figure 7.–Sensitivity analyses for model predictions of K_d-C_T and SD-C_T relationships, from uncertainty in component uncertainties, as ± 1 standard error of estimate of coefficients: a) a_p', for K_d-C_T relationship, b) a_p' for SD-C_T relationship, c) b' for K_d-C_T relationship, d) b' for SD-C_T relationship, e) N for SD-C_T relationship.

(Fig. 8). The average and range of $a_{y(440)}$ observations (Fig. 8a), and the best estimate and bound of + 1 standard error of the estimate of b (Fig. 8b) are provided for reference. The range of gelbstoff encountered in the lake corresponds to a modest change in K_d (<0.1/m; Fig. 8a). An approximate 2.5-fold increase in gelbstoff from the average concentration would increase K_d by about 0.2/m, or about 50% of the increase associated with an increase (a rather commonly observed fluctuation, Fig. 2a) of C_T from 5 to 30 mg/m^3 (Fig. 8a). Such an increase in gelbstoff could only occur as a result of anthropogenic influences (Perkins and Effler 1996). A 3-fold decrease in gelbstoff concentration, which is unrealistic based on its terrigenous origins (Perkins and Effler 1996) for this system, would reduce K_d by only about 0.1 m^{-1}. However, it would give the lake a more blue color during clearing events (see Perkins and Effler 1996).

The predicted relationship between SD and tripton scattering (Fig. 8b) reaffirms the sensitivity of clarity to scattering. Modest increases in $b_c + b'$, associated with terrigenous particle loading or $CaCO_3$ precipitation events, decrease SD markedly. At C_T = 5 mg/m^3, an increase in tripton scattering of about 1.6/m would reduce SD by the same amount as an increase of C_T from 5 to 30 mg/m^3 (Fig. 8b). Such increases occur irregularly for both b' and b_c in Onondaga Lake (e.g. Fig. 2b).

The model is used here to evaluate relative contributions of the attenuating components to the distributions of K_d and SD observed in Onondaga Lake in 1988 (Fig. 9a and b). The general approach used in this analysis is similar to that applied often in mechanistic water quality modeling (e.g, Canale et al. 1995, DiToro and Connolly 1980, Martin et al. 1985), in which contributing processes (e.g., individual oxygen sink processes contributing to a depletion in dissolved oxygen) are sequentially suppressed to identify the relative importance of the various components to temporal distributions of measures of water quality. Here we resolve the relative importance of the various attenuating materials in regulating light penetration in Onondaga Lake by sequentially suppressing phytoplankton, tripton, calcite, and gelbstoff, within the framework of the calibrated optics model.

The SD analysis is presented in the form of 1/SD (Fig. 9b) to make it more directly comparable to the K_d analysis, and to avoid potentially misleading results for scenarios of sequential decreases in absorption and/or

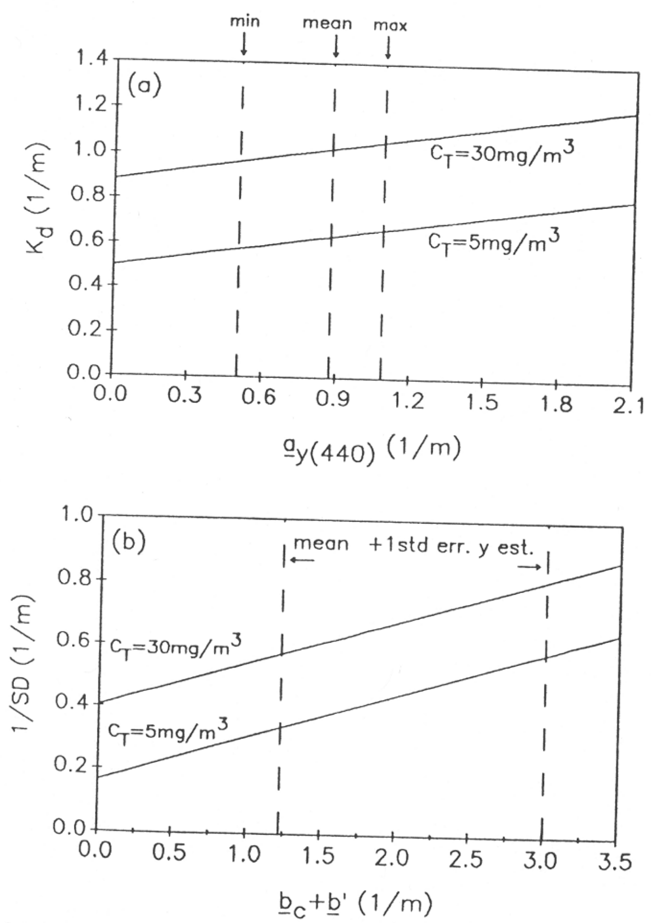

Figure 8.–Model predicted relationships for Onondaga Lake, for specified concentrations of C_T: a) K_d as a function of gelbstoff ($a_{y(440)}$), and b) 1/SD as a function of b'.

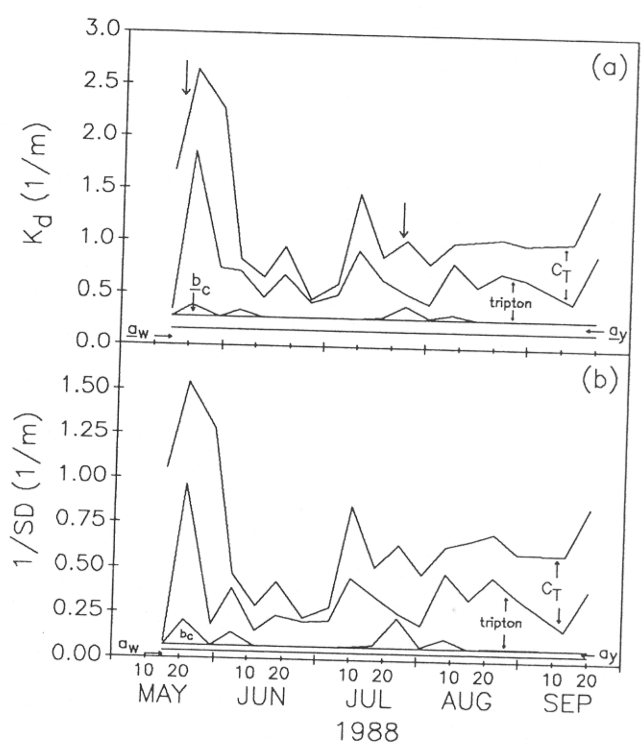

Figure 9.–Model analysis of contributions of components to attenuation and clarity in Onondaga Lake, for the conditions of 1988: a) K_d (arrows indicate occurrence of major runoff events), and b) 1/SD. "Tripton" refers only to the non-$CaCO_3$ components.

scattering at low levels of attenuation (causes very large incremental increases in SD, e.g., see Equation (9)). The predicted distributions of "observed" K_d and SD (presented as the top lines in Fig. 9) differ somewhat from the actual measurements (Fig. 2d and e), because they are generated with the model from the documented distributions of the attenuating components. The time distributions of the tripton components of absorption and scattering (non-$CaCO_3$) were first determined by difference (e.g., $a_p' = a - (a_w + a_y + K_a \cdot C_T)$). The sequence of suppression of attenuating components was $K_a \cdot C_T$ and $K_b \cdot C_T$ ($C_T = 0$, phytoplankton; i.e., simultaneously), a_p' and b' (tripton), b_c ($CaCO_3$, scatters without absorbing (Weidemann et al. 1985)), and a_y (gelbstoff). This order moves from (the top to bottom lines of Fig. 9a and b) the most manageable of the components, phytoplankton, to the least maneagable, gelbstoff.

The partitioning between phytoplankton and non-calcite tripton presented in this model analysis (Fig. 9) is imperfect, particularly because of temporal variations in the scattering and absorption characteristics of phytoplankton in the lake. For example, we suspect that the tripton contribution in August and September may be overestimated (Fig. 9). Despite these limitations, the analysis clearly demonstrates that the components primarily responsible for the limited light penetration in Onondaga Lake were phytoplankton and tripton (other than $CaCO_3$). Tripton (other than $CaCO_3$) can be dominant after a major runoff event. Gelbstoff and $CaCO_3$ were unimportant by comparison (Fig. 9). Note the greater relative contributions of a_y to K_d (Fig. 9a) and b_c to SD (Fig. 9b), consistent with theory (see Equations (8) and (9)). The partitioning analysis presented here for 1988 is generally representative of conditions for the entire 1987-1990 interval (Perkins and Effler 1996).

Management Perspectives

Onondaga Lake can be described as optically complex because of strong, uncoupled (independent and uncorrelated) variations in several light attenuating materials. These conditions dictated the development of a deterministic optics model to quantify the relative roles of attenuating materials in regulating light penetration (i.e., clarity). The model was successfully calibrated to the observed relationships between K_d, SD, and chlorophyll. The model was then used to evaluate the relative role of various materials in regulating prevailing light penetration conditions and the implications of changes in concentrations of gelbstoff and tripton. The modeling results demonstrate that management efforts to improve the clarity of the lake should focus on reduction of phytoplankton biomass; i.e., remediation of the lake's cultural eutrophication problem. This focus is appropriate not only because it is the most important component responsible for limited light penetration, but it is also the most subject to remediation. Improvements in clarity, achieved through reductions of phytoplankton biomass (e.g., reduction in external phosphorus loading), would be compromised irregularly, following runoff events, if terrigenous particle inputs are not abated.

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