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Secchi disk and photometer estimates of light regimes in Alaskan lakes: Effects of yellow color and turbidity

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Abstract

Variations in underwater light regimes among 58 Alaskan lakes were indexed by Secchi disk (SD) transparency and by vertical attenuation coefficients (K_d) and euphotic zone depths (EZD) derived from using a submarine photometer (SP) sensitive to photosynthetically active radiation (PAR). Lake-specific ratios between turbidity (light scattering) and color (light absorption) explained 52% of the variation ($P < 0.0001$) in $K_d \times$ SD values, which ranged as a continuum between 0.52 and 3.83. A clear-water median value of 1.86 (range, 1.13–3.26) is elevated by color to a median of 2.70 (range, 1.81–3.83), whereas turbidity reduces the median value of 0.93 (range, 0.52–2.56). EZD : SD, PAR at the SD depth, and PAR reflection (backscatter) also changed with the turbidity-to-color ratio. The nearly 10-fold ranges between $K_d \times$ SD (0.59–4.09) and EZD : SD (0.89–8.67) values taken from 35 studies on lakes, estuaries, and oceans could be explained by color and turbidity differences. Background attenuation from small amounts of color (<10 Pt units) and turbidity (<5 NTU) uncoupled SD and SP measurements from changes in Chl *a*, limiting their use as an index of trophic state. Changes in $K_d \times$ SD can serve, however, as a useful index of system loading by turbid particulate material or organic color.

Changes in water transparency [Secchi disk (SD) depth] have often been related to single factors, e.g. dissolved and colloidal organic matter or color (Schindler 1971), turbidity from suspended inorganic particulates (Zettler and Carter 1986), and phytoplankton (Ostrofsky and Rigler 1987). Although recognizing that each specific component reduces transparency, linkages to Chl *a* levels are often emphasized because of concerns over water quality (Carlson 1977).

Underwater light regimes have also been characterized using a submarine photometer (SP) to measure the attenuation of photosynthetically active radiation (PAR). The vertical attenuation coefficient (K_d) is a composite measure of PAR attenuation by water, suspended particles, Chl *a*, and organic color (Lorenzen 1980; Megard et al. 1980). Recent attempts at partitioning the composite K_d among these causative components have demonstrated the importance of changes in nonalgal or background attenuation (Elser 1987; Bowling 1988).

As both the SD and SP are used to assess underwater light regimes, a standard conversion between K_d and SD depth was developed, e.g. $K_d \times \text{SD} \approx 1.7$ (Poole and Atkins 1929). Viewed as universally applicable, other values (e.g. 1.44 and 1.16) derived from various bodies of water and proposed as substitutes (Holmes 1970; French et al. 1982, respectively) were either rejected (Idso 1982) or dismissed as trivial because no fundamental relationship exists between the two (Priesendorfer 1986).

Because light scattering (turbidity) and absorption (color) may act independently, each could evoke responses unique to the SD and SP, and the relative amount of each component could provide an index to the principal light-attenuating component (Kirk 1981*a,b*; Weidemann and Bannister 1986; Davies-Colley and Vant 1988). Different numerical factors relating SD to both K_d and EZD (euphotic zone depth), derived from previous studies, may then represent discrete parts of a continuous function that responds to unique amounts of turbidity, color, and Chl *a*. Defining the causal mechanism underlying that continuum has been complicated by a lack of paired SD and SP measurements from water bodies varying in levels of turbidity and color as well as Chl *a*.

Our purpose here is to evaluate SP and SD conversion factors (e.g. $K_d \times$ SD) as functional variables empirically predictable from specific mixtures of color, turbidity, and Chl *a*. The attenuation of light by color and turbidity, relative to Chl *a*, was assessed with paired SD and SP readings from 58 oligotrophic Alaskan lakes. These lakes were also grouped into three classes: turbid lakes, cloudy with silt, had little color; stained lakes, yellow from organic acids, had no turbidity; and clear lakes held little color or turbidity (Koenings et al. 1990). To define the generality of our approach, we compared EZD:SD and $K_d \times$ SD values from Alaskan lakes with those from 32 Canadian lakes and from 35 studies where lakes, estuaries, and oceans were classified similarly by apparent levels of color and turbidity.

Methods and materials

Sample collection—The 58 lakes (88 points: ~50% of the lakes were sampled for 2 yr) were located across a broad geographic region of Alaska extending from about 55°N, 130°W in the southeast panhandle, north to 62°N, 150°W on the Kenai Peninsula, and west to 57°N, 157°W on Kodiak Island. Because of the geographic range, numerous personnel collected the field data and water samples following procedures standardized by Koenings et al. (1987). In general, limnological sampling was conducted at a minimum of two midlake stations, and at 3-week intervals during the ice-free season (May–October). Water-quality samples were collected from the 1-m stratum with a Van Dorn sampler. The 8-liter bulk samples were stored <24 h in precleaned polyethylene carboys, prepared for laboratory analysis, and shipped to the limnology laboratory. Bulk water samples were subdivided as follows: refrigerated for turbidity measurement; frozen for total P analysis; and filtered through a Whatman 4.5-cm GF/F glass-fiber filter and then analyzed for color (Gordon and Wouters 1978; Kirk 1981*a*; Weidemann and Bannister 1986; Elser 1987).

Light penetration—SD transparency was determined as the averaged reading derived from lowering and raising a standard 20-cm-diameter, black-and-white disk from the shady side of the boat. Measurements of PAR penetration were taken with a Protomatic submarine photometer at 0.5-m intervals from the subsurface (0.05 m) to a depth of 5 m and at subsequent 1-m intervals to a maximum depth of 30 m or to the depth at which 1% of the subsurface PAR

Notation

K_d	Vertical attenuation coefficient, m^{-1}
PAR	Photosynthetically active radiation (400–700 nm)
EZD	Depth of penetration of PAR to 1% of incident levels (euphotic zone), m
EZD:SD	Ratio between depth of 1% light and depth that the Secchi disk disappears, unitless
$K_d \times$SD	Product of the vertical attenuation coefficient and the depth at which the Secchi disk disappears, unitless
R_f	Ratio of upwelling to downwelling PAR, %
TP	Total P, μg liter^{-1}
IPP	Inorganic particulate P, μg liter^{-1}
CTP	Total P minus IPP fraction, μg liter^{-1}
$I_{SD}:I_0$	Amount of incident PAR remaining at the SD depth, %
$I_m:I_0$	Amount of incident PAR remaining at 1 m, %

penetrates. The EZD, the depth at which 1% of incident light remains (Schindler 1971), was calculated as the *y*-intercept derived by regressing depth against the natural logarithm (ln) of the percent of incident PAR. The vertical attenuation coefficient [K_d, light retained (attenuated) per meter] was calculated as the reciprocal of the regression slope (Koenings et al. 1987). PAR reflectance (R_f) was determined as the mean of the ratio between the upwelling and downwelling irradiance taken at several depths in the water column, and expressed as a percentage. Reflectance coefficients from other studies, derived from upwelling and downwelling irradiances, were also converted into percentages and referred to as R_f. List of notation gives definitions and units.

Turbidity and color—Turbidity, expressed in nephelometric turbidity units (NTU), was determined with a model DRT-100 laboratory turbidimeter after allowing the samples to achieve room temperature. Daily calibrations were made with EPA-approved polymeric NTU standards. Specific color was determined on filtered samples by measuring absorbance at 400 nm with a spectrophotometer and then converting to platinum-cobalt (Pt) units (Koenings et al. 1987). NTU multiplied by a scaling factor of 10 and Pt units are used as empirical indices, respectively, of the PAR scattering

(b) and absorbance (a) coefficients derived in earlier studies (Kirk 1981a; Davies-Colley and Vant 1988).

Phosphorus—Total P (TP) was determined with the molybdenum-blue method as modified by Eisenreich et al. (1975) following acid persulfate digestion. Because glacial lakes are highly turbid, we corrected for the additional absorbance by analyzing turbidity blanks in conjunction with the samples (Koenings et al. 1987). TP was further corrected for the presence of "rock phosphate" or inorganic particulate P (IPP) using results from previous fractionation experiments on 10 clear (16 lake-years), 6 stained (10 lake-years), and 8 glacial lakes (Koenings et al. 1987). CTP (corrected TP) for each lake type was obtained from separate regressions. IPP represented ~40% of the TP of clear-water systems compared with only 12% in stained lakes and nearly 95% of the TP in turbid lakes.

Chlorophyll a—Seston samples for Chl a analysis were prepared by filtering a known volume, generally 0.5–1.0 liter, through a 4.25-cm GF/F filter to which about 2 ml of $MgCO_3$ were added before completion. Filters were stored frozen until analyzed by direct fluorometry (Koenings et al. 1990).

Statistical analysis—The Mann-Whitney U-test and the paired t-test, assuming unequal variances, were used to test for differences ($P < 0.05$) in median and mean values. Regressions were evaluated via F-tests on parametric regression slopes as well as by nonparametric Spearman rho (r_s) values. Regressions were also done in which the line was forced through the origin. ANCOVA was used to test for differences in slope between regression lines, and two-way ANOVA was used to estimate the amount of variation in optical factors caused by the method of calculation and by lake class. Finally, to define the underlying shape of the relationship between two variables, we used the nonparametric LOWESS (robust locally weighted regression) technique (Cleveland 1979). The LOWESS procedure uses locally weighted least-squares to fit a line to a scatter plot without the constraints of traditional regression. The weights (0.4) of data points are estimated iteratively with robust estimation techniques.

Results

Alaskan lake classification and characterization—Koenings et al. (1986, 1990) stratified Alaskan lakes into clear, stained, and turbid classes based on visually apparent color and turbidity. Clear lakes were in general characterized by low turbidities (<2 NTU) and minimal color (<10 Pt units), whereas stained lakes showed varying levels of color (>10 Pt units) and low turbidities (<3 NTU) (Table 1). In contrast, glacial lakes exhibited turbidities from <1 to 49 NTU and generally little color (<9 Pt units). We grouped lakes that are clear in spring but turbid in late summer, which resulted in the lowest seasonal mean turbidities, in the turbid category. The scaled NTU : Pt unit ratio was used as an objective measure of the relative importance of lake water to scatter and absorb PAR (Table 1). Across all lakes, scaled NTU : Pt units ranged from a low of 0.20 to a high of 116.7. The turbid lake median ratio was 16.2, which fell to 1.38 in clear lakes and to 0.44 in stained lakes.

Seasonal median levels of TP were highest in glacial lakes compared with both clear and stained lakes (Table 1). After correcting for IPP, however, CTP levels were higher in stained lakes compared with both clear and glacial lakes. Chl a levels ranged from median values of 0.6, 1.4, and 0.4 μg liter^{-1} in clear, stained, and glacial lakes. Chl a levels followed the pattern in CTP levels not TP. The low Chl a levels, as well as low CTP, found for Alaskan lakes (Table 1) characterize their oligotrophic status.

Optical characteristics—SD transparency ranged between 0.2 and 14.7 m, with median SD depths being lower in turbid lakes compared with median depths in both clear and stained lakes (Table 1). K_d ranged between 0.16 and 4.27 m^{-1}. Unlike SD transparency, the median value for K_d in stained lakes was equal to that of the turbid lakes and higher than the median K_d for clear lakes. This result suggests an unequal response of the SP and SD to changes in turbidity and color. PAR attenuation is affected equally by stain and turbidity, whereas SD transparency is particularly sensitive to turbidity.

Table 1. Alaskan lakes stratified into clear, stained, and turbid classes using apparent color and turbidity and showing lake-class differences between seasonal (May–October) median values based on selected water-quality parameters and optical characteristics. Medians for the lake classes are significantly different (Mann-Whitney *U*-test, $P < 0.05$) except as noted, *n* is number of lake years, and means are followed by the standard deviation (*in parentheses*).

Factors	Clear ($n = 44$)			Stained ($n = 21$)			Turbid ($n = 23$)		
	Range	Median	Mean	Range	Median	Mean	Range	Median	Mean
Water-quality parameters									
Color (Pt units)	2.3–16.4	7.9	7.7(2.8)	9.9–41.4	20.2	20.8(8.6)	2.5–12.8	6.1	6.2(2.3)
Turbidity (NTU)	0.2–2.0	0.9*	1.0(0.5)	0.3–3.0	1.0*	1.1(0.6)	0.8–49.0	8.0	17.8(18.1)
NTU : Pt×10	0.23–6.96	1.38	1.50(1.08)	0.20–2.46	0.44	0.63(0.54)	2.67–116.7	16.2	28.7(29.4)
TP (μg liter^{-1})	1.1–13.8	6.0	6.0(2.9)	2.4–19.3	10.2	10.0(0.8)	4.2–56.3	14.5	22.3(17.4)
CTP (μg liter^{-1})	2.3–9.8	5.1	5.2(1.7)	2.0–16.8	8.8	8.6(3.4)	1.5–4.1	2.0	2.4(0.9)
Chl *a* (μg liter^{-1})	0.2–5.6	0.6	1.1(1.2)	0.4–3.7	1.4	1.6(0.8)	0.1–1.3	0.4	0.5(0.3)
Optical characteristics									
SD (m)	2.3–14.7	6.9	7.2(2.7)	2.2–7.1	4.3	4.3(1.4)	0.2–3.9	1.5	1.5(1.2)
K_d (m^{-1})	0.16–0.63	0.27	0.31(0.12)	0.41–1.70	0.62*	0.70(0.07)	0.26–4.27	0.62*	1.63(1.51)
K_d×SD	1.13–3.26	1.86	1.99(0.54)	1.81–3.83	2.70	2.76(0.13)	0.52–1.77	0.93	1.05(0.31)
EZD (m)	7.4–27.9	16.1	16.4(5.1)	2.7–11.5	7.3*	7.4(0.5)	1.1–17.8	7.4*	6.5(5.0)
EZD : SD	1.3–3.9	2.42	2.41(0.61)	1.15–2.45	1.75	1.73(0.41)	2.61–8.67	4.93	4.97(1.39)
$I_{SD} : I_0$ (%)	0.8–18.2	7.4	7.5(4.3)	0.9–10.8	3.6	4.6(3.3)	8.5–36.3	21.7	21.2(8.0)
$I_m : I_0$ (%)	7.1–70.8	27.1	29.9(13.1)	7.9–36.9	19.9	21.3(9.7)	0.7–39.6	14.6	14.6(12.0)

* Not significantly different.

Optical factors—Values of $K_d \times$ SD, ranged from a low of 0.52 to a high of 3.83 (Table 1). In stained lakes the median $K_d \times$ SD equaled 2.70 compared with a median of 0.93 for turbid lakes and 1.86 for clear lakes. In general, median (and mean) $K_d \times$ SD values were lower in turbid lakes, but higher in stained lakes compared with clear-water lakes.

Changes in EZD between lake classes followed that described for K_d in that the median values of EZD for stained and turbid lakes were less than half the EZD of clear lakes. Analogous to the $K_d \times$ SD values EZD : SD ratios also differed among lake classes. In stained lakes, EZD : SD equaled 1.75 compared with a median value of 4.93 for turbid lakes and 2.42 for clear lakes. In nonturbid (clear + stained) lakes, EZD : SD averaged 2.08, i.e. the EZD was twice as deep as the SD depth.

The percent of the incident light (I_0) at the SD depth (I_{SD}) ranged between 0.8 and 36.3% and also varied by lake type (Table 1). The lowest median occurred in stained lakes (3.6%) compared with 7.4% in clear lakes and 21.7% in turbid lakes. The SD depth received significantly different levels of PAR depending on the degree of color and turbidity.

The percent of PAR reflected (R_f) was not measured in every lake included in the lake summary (Table 1); however, Koenings et al. (1986) reported mean reflectance levels for turbid (33.3%), clear (4.6%), and stained (1.7%) lakes. Thus, turbid lakes appeared to scatter or reflect more PAR compared with clear lakes, while stained lakes appeared to reduce scatter and absorb light.

Calculation differences in optical factors—Values obtained for both $K_d \times$ SD and EZD : SD were similar within each lake class, but were consistently different between lake classes (Table 2). Classifying EZD : SD and $K_d \times$ SD by lake type accounted for 67 and 97% ($P < 0.001$) of the variation compared with <4 and 2% ($P > 0.49$) when classed by method of calculation (two-way ANOVA, F-test). The largest deviations were in the slope of the clear-lake regressions because the y-intercepts were different from zero.

Table 2. EZD : SD and $K_d \times$SD values for clear, stained, and turbid lake classes determined using means, medians, and regressions with a significant or nonsignificant y-intercept (b) and forcing the y-intercept through the origin. Asterisks: **—$P < 0.01$.

Lake class	Lake-years	Mean	Median	Slope ($\pm b$)	Slope ($b = 0$)
		EZD : SD			
Stained	21	1.73	1.75	1.41(1.3)	1.68
Clear	44	2.41	2.42	1.35(6.7)**	2.16
Turbid	23	4.80	4.93	3.66(1.1)	3.66
		$K_d \times$SD			
Stained	21	2.76	2.70	2.84(0.0)	2.76
Clear	44	1.99	1.86	1.20(0.1)**	1.77
Turbid	23	1.05	0.93	0.93(0.1)	0.97

Effect of Chl a, *color, and turbidity on SD transparency*—A strong correlation ($r_s = 0.84$; $P < 0.005$) was found between EZD and SD transparency when all lakes were included (EZD = 2.96 + 1.73 SD; $r^2 = 0.70$; $P < 0.0001$). Similarly, a strong correlation ($r_s = 0.84$; $P < 0.005$) exists between K_d and SD^{-1} ($K_d = 0.24 + 0.902$ SD^{-1}; $r^2 = 0.89$; $P < 0.0001$) when all lakes were considered. The slopes of the regression lines of individual lake classes were different (ANCOVA, $P < 0.0001$), however, suggesting fundamental differences between SD and SP conversions based on relative differences in Chl a, color, and turbidity.

Considering all lakes, 83% of the variation in 1/SD was accounted for by turbidity (Table 3). Chl a levels explained 5% of the variation, but the regression exhibited a negative slope, i.e. increases in SD transparency were coupled with increases in Chl a. Because of the weak correlation ($r^2 = 0.05$) this is likely a statistical anomaly as the Spearman r_s was not significant, and stepwise multiple regression included only turbidity as the significant variable. In contrast, in clear lakes, Chl a accounted for 59% of the variation in 1/SD, turbidity explained 32%, and color was not significant. In stained lakes, color explained 49% of the variation in 1/SD, and both turbidity and Chl a failed to explain further variation. In turbid lakes, turbidity accounted for 73% of the 1/SD variation, and both color and Chl a were not significant.

Effect of Chl a, *color, and turbidity on* K_d—Considering all lakes, turbidity explained 93% of the variation in K_d, turbidity

Table 3. The variation in SD depth explained (r^2) by Chl *a*, color (Pt units), and turbidity (NTU) in clear (n = 44), stained (n = 21), and turbid (n = 23) lakes, and all lakes (n = 88) combined using either single-factor regression or multiple regression techniques. Degree of significance was determined with an F-test (two-tailed) with ns denoting nonsignificance.

Lake classes	1/SD (Y) vs.			
	Chl *a* (μg liter^{-1})	color (Pt units)	turbidity (NTU)	stepwise multiple regression
Clear	$Y = 0.11 + 0.047$Chl *a* $r^2 = 0.59$; $P < 0.0001$	ns	$Y = 0.07 + 0.091$turbidity $r^2 = 0.32$; $P < 0.0001$	$Y = 0.07 + 0.039$Chl *a* $+ 0.05$turbidity $r^2 = 0.65$; $P < 0.0001$
Stained	ns	$Y = 0.10 - 0.007$color $r^2 = 0.49$; $P = 0.0004$	ns	$Y = 0.10 + 0.007$color $r^2 = 0.49$; $P = 0.00004$
Turbid	ns	ns	$Y = 0.061$turbidity $r^2 = 0.73$; $P < 0.0001$	$Y = 0.061$turbidity $r^2 = 0.73$; $P < 0.0001$
All lakes	$Y = 0.83 - 0.226$Chl *a* $r^2 = 0.05$; $P = 0.03$	ns	$Y = 0.18 + 0.068$turbidity $r^2 = 0.83$; $P < 0.0001$	$Y = 0.18 + 0.068$turbidity $r^2 = 0.83$; $P < 0.0001$

Table 4. As Table 3, but of K_d values.

Lake classes	K_d (Y) vs.			
	Chl *a* (μg liter^{-1})	color (Pt units)	turbidity (NTU)	stepwise multiple regression
Clear	$Y = 0.26 + 0.047$Chl *a* $r^2 = 0.23$; $P < 0.001$	$Y = 0.19 + 0.015$color $r^2 = 0.14$; $P = 0.01$	$Y = 0.22 + 0.089$turbidity $r^2 = 0.12$; $P < 0.02$	$Y = 0.13 + 0.049$Chl *a* $+ 0.016$color $r^2 = 0.39$; $P < 0.0001$
Stained	ns	$Y = 0.034$color $r^2 = 0.78$; $P = 0.0001$	ns	$Y = 0.034$color $r^2 = 0.78$; $P = 0.0001$
Turbid	$Y = 3.12 + 2.567$Chl *a* $r^2 = 0.17$; $P = 0.04$	ns	$Y = 0.093$turbidity $r^2 = 0.95$; $P < 0.0001$	$Y = 0.093$turbidity $r^2 = 0.95$; $P < 0.0001$
All lakes	ns	ns	$Y = 0.29 + 0.090$turbidity $r^2 = 0.93$; $P < 0.0001$	$Y = 0.05 + 0.090$turbidity $+ 0.031$color $r^2 = 0.96$; $P < 0.0001$

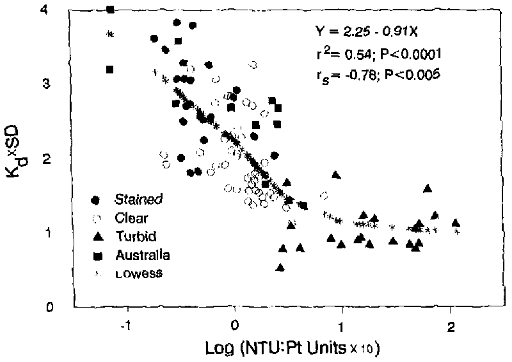

Fig. 1. The inverse relationship between $K_d \times$ SD values and the scaled turbidity-to-color ratio from stained, clear, and turbid Alaskan lakes and nonturbid Australian lakes. Also shown are the nonparametric LOWESS scatterplot smoothing points that form a continuum through the range in $K_d \times$ SD values.

and color combined to account for 96% of the variation, and Chl *a* was not significant (Table 4). In contrast, in clear lakes changes in Chl *a* levels did explain 23% of the variation in K_d values, while Chl *a* and color together explained 39%. In stained lakes, color accounted for 78% of the changes in K_d, but both Chl *a* and turbidity failed to explain further variation. Finally, in turbid lakes, turbidity explained 95% of the variation in K_d values, and both color and Chl *a* failed to enter the multiple regression model.

Color and turbidity and the $K_d \times$ *SD continuum*—Because all-lake regression models correlating changes in both K_d and 1/SD did not include Chl *a* as a significant variable (Tables 3 and 4), we evaluated the relationship of color (Pt units) and turbidity (NTU) to changes in the value of $K_d \times$ SD (Fig. 1). By using the LOWESS smoothing procedure, we found that $K_d \times$ SD values defined a continuous function when related to the log of the ratio between turbidity and color. The underlying shape of the continuum was linear across the nonturbid (clear + stained) lakes, but there appears to be a breakpoint at a value of ~0.7 log (NTU : Pt) units where the curve flattens, i.e. at high levels of turbidity the ability to measure minor changes in SD depth is small. In Alaskan lakes, a significant linear relationship exists between the log of the NTU : Pt ratio and of $K_d \times$ SD (Fig. 1).

The same basic continuum of changes in $K_d \times$ SD with the turbidity-to-color ratio observed in Alaskan lakes was observed in northeast U.S. (Weidemann and Bannister 1986) and Australian (Bowling 1988) lakes. Even though the three clear lakes studied by Weidemann and Bannister exhibited a much smaller range in both $K_d \times$ SD values (0.90–1.91) and turbidities (1.76–4.80 NTU), the relationship between higher $K_d \times$ SD values and a lower NTU : a_y ratio in northeast lakes was significant ($r_s < -0.43$; $P < 0.05$). In 12 Australian lakes, color (after conversion to Pt units) ranged from 2.2 to 137.1 Pt units while turbidities were low (0.5–3.0 NTU), but $K_d \times$ SD ranged between 1.37 and 4.09. Like Alaskan lakes, Australian lakes with the most stain had the highest $K_d \times$ SD values ($r_s = -0.74$; $P < 0.005$), clearer systems had lower $K_d \times$ SD values, and the log of the scaled NTU : Pt ratio accounted for 64% of the variation in $K_d \times$ SD. Finding no significant difference between the Alaskan and Australian regressions (ANCOVA; $P = 0.65$), we combined the data sets into a common regression (Fig. 1).

Color and turbidity and the EZD : SD continuum—Like the $K_d \times$ SD continuum, the log of the scaled NTU : Pt ratio explained 53% of the variation in EZD : SD values: EZD : SD = 2.41 + 1.58 log (NTU : Pt); $r^2 = 0.53$; $P < 0.0001$. Unlike the negative slope of the $K_d \times$ SD relationship, however, an increase in the turbidity-to-color ratio is accompanied by a deeper EZD relative to the SD depth. The largest median EZD : SD value was for turbid lakes and the lowest for stained lakes (Table 2).

Color and turbidity and PAR at the SD depth—Across all Alaskan lakes, the scaled NTU : Pt ratio accounted for 75% of the variation in the percent of incident light at the SD depth ($I_{SD} : I_0$) (Fig. 2). An increase in the log of the NTU : Pt ratio is accompanied by an increase in the amount of incident light at the SD depth ($r_s = 0.82$). Thus, for all lakes an increase in the $K_d \times$ SD value should be accompanied by a decrease in the $I_{SD} : I_0$ ratio—exactly what we found ($r_s = -0.84$) (Fig. 3). Clear-water lakes were intermediate in value between the upper and lower extremes established by the stained

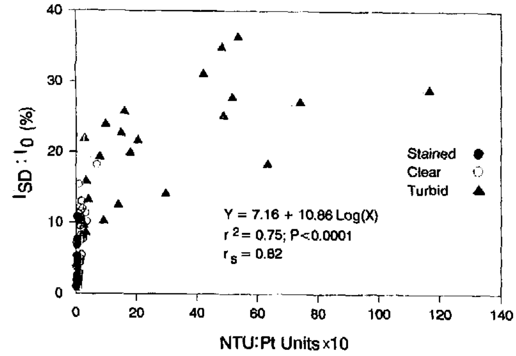

Fig. 2. The direct, continuous relationship between the amount of surface PAR present at the SD depth ($I_{SD}:I_0$), expressed as a percent, and the scaled turbidity-to-color ratio for stained, clear, and turbid Alaskan lakes.

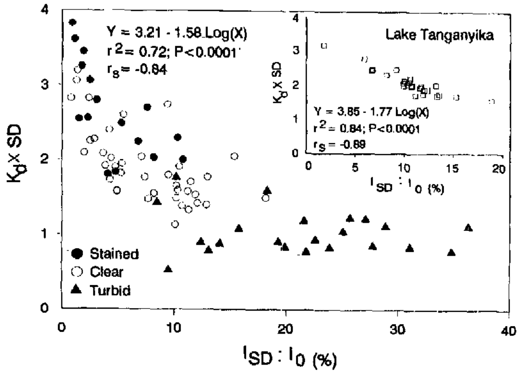

Fig. 3. The continuum that exists between $K_d \times$ SD values and the percent of surface PAR present at the SD depth ($I_{SD}:I_0$), expressed as a percent, for stained, clear, and turbid Alaskan lakes. Also shown is an equivalent relationship derived with data from Lake Tanganyika (Hecky et al. 1978).

and turbid systems, respectively. We calculated a range (1.58–3.17) for $K_d \times$ SD values from Lake Tanganyika, and $I_{SD}:I_0$ values ranged from 1.8 to 18.8% (Hecky et al. 1978). The same (ANCOVA; $P = 0.63$) continuum existed ($r_s = -0.89$) between $K_d \times$ SD and $I_{SD}:I_0$ values in Lake Tanganyika (Fig. 3) as found for Alaskan lakes (Fig. 3).

PAR reflectance (R_f) *and the* $K_d \times$ *SD continuum*—We calculated the $K_d \times$ SD values for 28 New Zealand lakes and found that nearly two-thirds ($r^2 = 0.63$) of the variation in $K_d \times$ SD was explained by R_f ($r_s = -0.78$; $P < 0.005$). New Zealand lakes identified as turbid had the lowest $K_d \times$ SD values and the greatest R_f, while stained lakes had the highest $K_d \times$ SD and the lowest R_f. Also, R_f explained nearly 75% of the variation in $K_d \times$ SD values from northeast U.S. (Weidemann and Bannister 1986) and Australian (Bowling 1988) lakes. Overall, stained lakes with high median $K_d \times$ SD values (2.30–2.70) had low R_f values (1.1–1.7%), turbid lakes with low $K_d \times$ SD values (0.60–0.93) had higher R_f values (33.3–34%), and clear lakes were intermediate in both parameters (Table 5). There were no significant differences in regression slopes of the three data sets (ANCOVA; $P = 0.09$), and the pooled data resulted in a single, highly significant relationship (Fig. 4A).

R_f *and levels of turbidity and color*—Mean R_f values for turbid (33.3%), clear (4.6%), and stained (1.7%) Alaskan lakes from Koenings et al. (1986) were combined with median $K_d \times$ SD values for these lake types (0.93, 1.86, and 2.70, respectively) from Table 1. In Alaskan lakes, R_f levels were higher in turbid lakes with the largest NTU : Pt ratio and lower in stained lakes that exhibited the lowest ratio (Fig. 4B). Northeast U.S. (Weidemann and Bannister 1986) and Australian (Kirk 1981*b*; Bowling 1988) lakes all showed a positive relationship between R_f and a turbidity-to-color ratio unique to each

Table 5. Lake classes, and appropriate $K_d \times$SD and R_f values determined from lakes in New Zealand (Davies-Colley and Vant 1988), Australia (Kirk 1976, 1981*a*; Bowling 1988), the northeast U.S. (Weidemann and Bannister 1986), and Alaska (Koenings et al. 1986) compared to those found in the present study.

Lake class	$K_d \times$SD	R_f (%)
Stained		
Davies-Colley and Vant	2.30	1.3
Bowling	2.58	1.1
Koenings et al.	—	1.7
Present study	2.70	—
Clear		
Weidemann and Bannister	1.49	4.1
Davies-Colley and Vant	—	~5.0
Koenings et al.	—	4.6
Present study	1.86	—
Stained and turbid		
Kirk	—	9.9
Turbid		
Davies-Colley and Vant	0.60	34.0
Koenings et al.	—	33.3
Present study	0.93	—

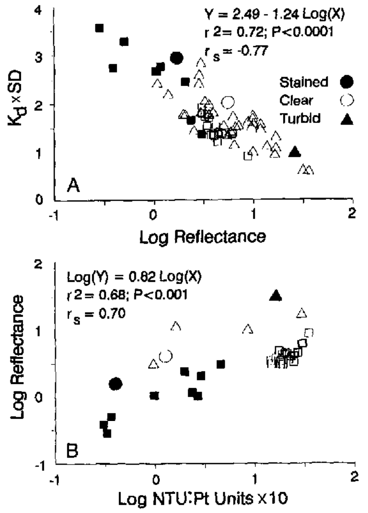

Fig. 4. A. The inverse relationship between $K_d \times$ SD values and PAR reflectance (R_f) from lakes in New Zealand (Davies-Colley and Vant 1988—△), Australia (Bowling 1988—■), and the northeast U.S. (Weidemann and Bannister (1986—□), and Alaskan lake medians. B. The direct relationship between PAR reflectance (R_f) and the scaled turbidity-to-color ratio for Australian lakes (Kirk 1976—△; Bowling 1988—■) and for Alaskan lake class medians. Also shown is the data scatter for northeast U.S. lakes (Weidemann and Bannister 1986—□) which are not included in the overall regression.

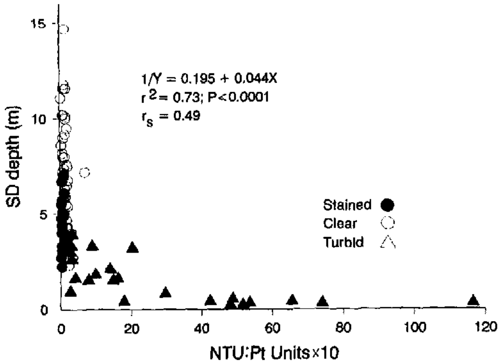

Fig. 5. The continuous, inverse relationship between the SD depth and the scaled turbidity-to-color ratio for stained, clear, and turbid Alaskan lakes.

study. Moreover, we converted Bowling's (1988) estimate of color (gilvin units) into Pt units and also used data from several lakes of Kirk (1976, 1981*a*). With the Alaskan lake medians included, the common regression slope was highly significant (Fig. 4), and over two-thirds of the variation in R_f (ranging from 0.3 to 33.3%) was caused by changes in turbidity (0.53–49 NTU) and color (2.2–137.1 Pt units).

Discussion

The SD depth and nonalgal light attenuation—Using a theoretical approach, Lorenzen (1980) and Megard et al. (1980) argued that changes in SD transparency could be linked to Chl *a* levels only in the absence of nonalgal light attenuation. In Australian dune lakes <2% of the variation in K_d could be explained by Chl *a* compared to 81% by yellow color (Bowling 1988), and Elser (1987) found total amounts of Chl to be unrelated to changes in K_d when compared with dissolved color for northern Wisconsin and Michigan lakes. In the North Pacific Ocean, K_d values were significantly correlated to particulate matter, but not to Chl *a* (Otobe et al. 1977). In Alaskan lakes with low amounts of color (2.3–41.4 Pt units) and turbidities (0.2–49 NTU), nearly 75% of the variation in 1/SD could be explained by the scaled turbidity-to-color ratio (Fig. 5). Neither 1/SD or K_d correlated with Chl *a* except in the absence of both color and turbidity, i.e. in clear lakes (Tables 3 and 4); and, despite levels of Chl *a* characteristic of oligotrophic lakes, the median SD transparency of 1.5 m of turbid lakes was less than the minimal 3.7-m depth used to index oligotrophy (Wetzel 1975). Thus, only the lack of nonalgal light attenuation (e.g. clear lakes) allows a functional relationship of either SD depths or K_d to Chl *a* levels ranging between 0.2 and 5.6 μg liter^{-1} (Tables 1 and 3). Given seasonal and annual variation in both color and turbidity, the use of SD to assess either changes in Chl *a* or linkages to trophic state can be made only when color and nonalgal turbidity have been shown to be either unimportant or unchanged.

The SD depth and PAR intensity—As PAR attenuates with depth, primary production reaches a peak near the mideuphotic zone (Talling 1971; Smith 1979). The proportion of incident light reaching the SD depth is commonly accepted to range between 5 and 15% or ~10% (Beeton 1957; Tyler 1968; Megard et al. 1980), and as such the SD depth has been used to estimate the mideuphotic zone. Because of varying levels of

Table 6. Summary of $K_d \times SD$, EZD : SD, and $I_{SD} : I_0$ values from lakes, estuaries, and oceans located throughout the world grouped into stained, clear, and turbid classes based on the site description of the investigators. Also given are the geographical locations and specific site descriptions taken from the cited sources.

Reference	$K_d \times SD$	EZD : SD	$I_{SD} : I_0$ (%)	Location	Site description
			Stained		
Birge and Juday 1934	–	–	5.0	Northern Wisconsin	Acid bog (humic stained) lakes
Bowling 1988	2.34	1.27	–	SE Australia	Coastal dune (humic stained) lakes
Bowling and Tyler 1986	3.97	–	–	Fidler Lake, Tasmania	"Backswamp" (humic stained) type
Davies-Colley and Vant 1988	2.3	–	–	Lakes D and Rotomanuka, N.Z.	"Dark," humic stained
Edmundson et al. 1989	–	0.89	–	Finger Lake, Alaska	Humic stained
Effler 1985	2.33	–	–	Dart Lake, N.Y.	Acidified, gelbstoff present
Effler and Auer 1985	>3.0	–	–	Green Bay, Lake Michigan	Gelbstoff influence from rivers
Fee et al. 1989	2.5	1.48	2.8	Red Lake District, NW Ontario	Yellow-brown lakes
Graham 1966	3.9	–	–	N. Pacific (*Manning* Cruise 36)	Seawater, riverine influence
Hecky 1984	2.8	–	–	Wood Lake, northern Manitoba	Boreal forest
Jackson and Hecky 1980	3.19	–	–	Notigi Res., Manitoba	Boreal forest lake, postimpoundment
Present study	2.70	1.75	3.6	Alaska	Subarctic, humic-stained lakes
Schindler 1971	3.45	–	–	ELA lakes, Ontario	Humic stained
Stockner and Cliff 1976	3.58	–	–	Howe Sound (S-3), B.C.	Seawater, stained by pulp mill effluent
Stockner and Shortreed 1978	3.01	1.55	–	B.C. and Yukon Territory	Humic-stained lakes
Walker 1982	2.4	–	–	NE Australia	Seawater, dilution by river
Zadina and Haddix 1991	3.34	1.32	1.3	SE Alaska	Humic-stained lakes
			Clear		
Beeton 1957	1.9	–	14.7	Lake Huron	Clear water
Carlson 1977	–	–	10.0	New York lakes, Lake Washington	Clear water
Clarke 1941	–	–	15.2	N. Atlantic	Seawater
Graham 1966	1.5	–	–	N. Pacific (*Manning* Cruise 32)	Seawater
Hecky 1984	1.52	–	–	Southern Indian Lake, Manitoba	Preimpoundment
Hecky et al. 1978	2.02	–	10.8	Lake Tanganyika	Clear water, tropical
Hobbie 1973	1.9	–	–	Unnamed lake, eastern Greenland	Clear water
Kikuchi 1937	1.91	2.41	8.4	Japan	Temperate lakes
Kling 1988	1.61	–	–	Cameroon	Tropical lakes
Present study	1.86	2.42	7.4	Alaska	Subarctic, clear-water lakes
Poole and Atkins 1929	1.7	–	15.8	English Channel	Seawater
Sakamoto 1966	1.9	–	–	Japan	Clear-water lakes
Stockner and Cliff 1976	1.9	–	–	Howe Sound (S-6)	Seawater, no pulpmill effluent stain
Stockner and Shortreed 1978	1.90	2.46	–	B.C. and Yukon Territory	Clear-water lakes
Tyler 1968	–	–	10.0	N. Pacific	Seawater
Weidemann and Bannister 1986	1.8	–	–	Oneida Lake, N.Y.	Clear water

Table 6. Continued.

Reference	$K_d \times SD$	EZD : SD	$I_{SD} : I_0$ (%)	Location	Site description
			Turbid		
Davies-Colley and Vant 1988	0.59	—	—	Lakes Tekapo and Pukaki, N.Z.	"Bright," turbid glacial
Effler 1985	1.31	—	—	Otisco Lake, N.Y.	Presence of $CaCO_3$ "whiting" (turbidity)
French et al. 1982	1.16	2.81	—	Lahontan Res. and others, U.S.	Artificial impoundments
Golterman 1975	—	—	>20	Lake Gjende, Finland	Turbid glacial
Hecky 1984	1.26	—	—	Southern Indian Lake	Postimpoundment
Holmes 1970	1.44	3.2	22.6	Goleta Bay, N. Pacific	Turbid, coastal waters
Hunter and Wilhm 1984	—	—	>30	Keystone Lake, Oklahoma	Impoundment, nonalgal turbidity
Jackson and Hecky 1980	0.91	—	—	Southern Indian Lake	South bay contains suspended clay
Present study	0.93	4.93	21.7	Alaska	Subarctic, turbid glacial lakes
Marzolf and Osborne 1972	1.62	—	—	Tuttle Cr. Res., Kansas	Presence of sediment turbidity
Otobe et al. 1977	1.47	3.2	~25	Bering Sea and N. Pacific	Presence of scattering particulate matter
Stockner and Shortreed 1978	1.46	3.38	—	B.C. and Yukon Territory	Turbid glacial lakes
Stockner and Shortreed 1983	—	4.4	—	Five glacial lakes, Fraser River system, B.C.	Presence of glacial turbidity
Walker 1982	1.46	—	—	NE Australia	Coastal seawater, estuarine
Weidemann and Bannister 1986	0.9	—	—	Otisco Lake	Presence of $CaCO_3$ "whiting"

color and turbidity (Fig. 4), however, PAR levels at the SD depth are not comparable (Table 1). In clear lakes about 7.4% of PAR occurs at the SD depth—close to the 10% figure generally used as the traditional assumption (Megard et al. 1980). In stained lakes, however, a median of only 3.6% of PAR is available, and in turbid lakes PAR at the SD depth increases to nearly 22% of incident light. At 1 m, median light levels equal 27% of incident PAR in clear lakes compared to 20 and 15% in stained and turbid lakes. Attempts to equalize light levels for photosynthesis experiments by incubating at the SD depth thus seem to offer little advantage over a constant incubation depth (Table 1).

The mechanism underlying the $K_d \times$ *SD continuum*—In Alaskan lakes, the NTU : Pt ratio explains much of the variation in the EZD : SD and $K_d \times$ SD values (Fig. 1). Similarly, Gordon and Wouters (1978) argued that $K_d \times$ SD values (range, 0–4) are strongly dependent on the optical properties of any waters' suspended particles and dissolved absorbers. Davies-Colley and Vant (1988) theorized that $K_d \times$ SD values (range, 0.5–4) from New Zealand lakes were functions of both the ratio of scattering to absorption and percent R_f, and Effler and Auer (1985) suggested that $K_d \times$ SD values (range, 1.6–3.6) from Green Bay (Lake Michigan) may be caused by differences in dissolved color. In marine systems, Holmes (1970) found the median EZD : SD value for turbid coastal waters of the U.S. equaled 3.2 (range, 2.0–4.1) and suggested that a value closer to 2.0 may be appropriate for less turbid waters. Finally, Walker (1982) noted that $K_d \times$ SD values in nearshore ocean waters off Australia increased as dissolved organics increased, but this shift was masked in regions with suspended sediments (turbidity).

It is important to note that the turbidity (0.53–49 NTU) and color ranges (2.2–41.4 Pt units) for Alaskan lakes which nearly cover the entire $K_d \times$ SD range of 0.5–4.0 (Fig. 1) are not excessive (e.g. Brezonik 1978 listed a value of 550 Pt units for a Florida

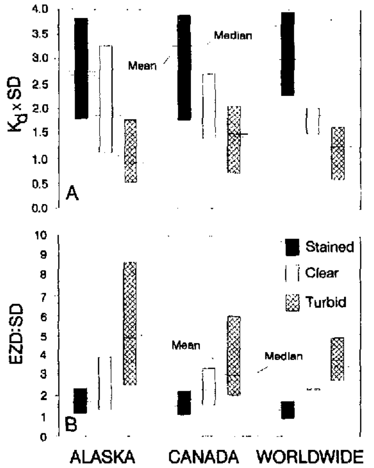

Fig. 6. Comparison of K_d × SD and EZD : SD values (mean, median, and range) from Alaskan lakes (Table 1) with Canadian lakes (Stockner and Shortreed 1978) and other lake, estuarine, and oceanic waters (*see Table 7*) classified by apparent levels of color and turbidity into clear, stained, and turbid waters.

lake). Color and turbidity values higher than we found for Alaskan lakes may be sufficient to nearly saturate the SD, but not the SP. Consequently, we suspect that at each end of the K_d × SD continuum the relationship will flatten out as already suggested by the LOWESS curve at higher turbidity-to-color ratios (Fig. 1). Because of this saturation, the regression of either K_d and 1/SD or EZD on SD from stained and turbid lakes results in a zero intercept. In contrast, the SP and SD cannot be saturated in clear-water, oligotrophic lakes and regression results in nonzero intercepts (Table 2).

K_d × *SD, EZD : SD, and* $I_{SD} : I_0$ *values in lakes, estuaries, and oceans*—Values of K_d × SD, EZD : SD, and $I_{SD} : I_0$ in Alaskan lakes changed with the relative amounts of color and turbidity (Figs. 1 and 2), which was reflected in the stained, clear, and turbid lake classes (Table 1). Because concomitant turbidity, color, and SD transparency and SP light measurements are uncommon, K_d × SD and EZD : SD values from 32 lakes in Canada (Stockner and Shortreed 1978) and from 35 studies on lakes, estuaries, and oceans were also separated, using the investigator's description, into stained, clear, and turbid classes (Table 6).

Table 7. Comparison of K_d×SD, EZD : SD, $I_{SD} : I_0$, and R_f median values from stained, clear, and turbid water bodies located throughout the world, and the ratio of turbidity to color determined for Alaskan lakes. Consensus optical factors are derived from lakes, estuaries, and oceans as listed in Tables 5 and 6.

Parameter	Stained	Clear	Turbid
K_d×SD	3.0	1.9	1.3
EZD : SD	1.3	2.4	3.3
$I_{SD} : I_0$ (%)	3.2	10.4	22.6
R_f (%)	1.4	4.6	33.7
Turbidity (×10) : color	0.4	1.4	16.2

Within each set of Alaskan, Canadian, and other water bodies, the respective K_d × SD (Fig. 6A) values followed equivalent patterns, and the overall ranges were very consistent. Median K_d × SD values of the stained, clear, and turbid classes within each data set were significantly different ($P < 0.01$). However, there were no significant differences ($P > 0.05$) between the median K_d × SD values for stained, clear, and turbid classes across the Alaskan, Canadian, and other water bodies except between turbid lakes in Alaska and Canada. The overall range for K_d × SD values (Figs. 1 and 6A) suggests an upper boundary at ~4.00 and a lower boundary at ~0.50.

Median EZD : SD (Fig. 6B) values for the Alaskan, Canadian, and other water bodies also followed equivalent patterns; and the overall ranges, except for the less numerous worldwide systems, were very similar. Within each of the three data sets, the EZD : SD medians for the lake classes were different ($P < 0.05$), except for the clear and turbid class medians within the Canadian and worldwide systems. There were no differences in lake-class medians between data sets, except between the Alaskan and both the Canadian and worldwide turbid classes. The overall range for EZD : SD values (Fig. 6B) suggests an upper limit of 10.0 and a lower boundary of 1.0.

Consensus values for optical factors—Consensus values (Table 7) for K_d × SD and other optical factors were derived for stained, clear, and turbid water bodies from median values in Tables 5 and 6. In general, values for clear water bodies were consistent with traditional assumptions. The median K_d × SD value of 1.90 is from clear-water

Lake Huron (Beeton 1957), the $I_{SD}:I_0$ value of 10.4% is very close to the traditional assumption of 10% (Megard et al. 1980), the EZD : SD value of 2.42 is consistent with the rule of thumb that the EZD is 2.4 times the SD depth (Smith 1979), and a R_f of 4.6% is close to the 5% value suggested for clear-water New Zealand lakes by Davies-Colley and Vant (1988).

Forcing functions of both color and turbidity significantly alter these traditional assumptions, derived from clear water bodies, into values more appropriate to stained (Pt units > 10) and turbid (NTU > 5) waters (Table 7). The shift of an EZD : SD from 3.2 in turbid ocean waters to about 2.0 in clearer waters puzzled over by Holmes (1970) now has a likely explanation. Also less problematic are the differences in $I_{SD}:I_0$ values from the traditional assumptions of 5, 10, and 20% (Hobbie 1973; Megard et al. 1980; Lorenzen 1980). Instead of such divergence being caused by differences in electronic instrumentation (Beeton 1957; Wetzel 1975), they reflect where the original data were taken. The 5% figure comes from the humic-stained lakes in northern Wisconsin and Michigan (Birge and Juday 1934), the 10% value from clear-water lakes (Carlson 1977) (and by averaging the 5% value with the 15% figure of Beeton 1957), and the 20% value from turbid systems, e.g. the turbid seawater value of 23% (Holmes 1970).

The SD depth, and K_d *and EZD*—Even though the NTU : Pt ratio accounted for 73% of the variation in water transparency (Fig. 5), no significant relationship was found between the NTU : Pt ratio and either K_d or EZD. In both the stained and turbid lakes, the median EZD decreased to 7.3 m compared with the clear lake median of 16.1 m. The median SD depth for clear lakes of 6.9 m decreased, however, to 4.3 m in stained lakes and to 1.5 m in turbid lakes because of the particular sensitivity of the SD to turbidity. The differential shift in SD transparency in response to changes in color and turbidity underlies the significance of the relationship between the NTU : Pt ratio and SD depth (Fig. 5) and causes $K_d \times$ SD values to vary continuously and inversely with the scaled NTU : Pt ratio (Fig. 1). Neither the SD or SP can differentiate between color- or turbidity-mediated changes in water transparency or PAR attenuation. Yet, the response of both instruments, expressed as $K_d \times$ SD (or EZD : SD), has diagnostic use because increases in turbidity lower $K_d \times$ SD values while increases in color raise them.

Applications of paired SD and SP measurements—Hecky (1984) studied the optical history of Southern Indian Lake before and after impoundment. Both the SP and SD were used to characterize the light regimes of Southern Indian Lake and the control, Wood Lake. After impoundment, Southern Indian Lake underwent visual changes in turbidity and the K_d values significantly increased from 0.84 to 1.35 m^{-1}. SD depths correspondingly decreased from 1.65 to 0.85 m, and $K_d \times$ SD values decreased from 1.54 to 1.15 which is consistent with our empirical generalizations, i.e. the direction of change would suggest movement from clear-water conditions to turbid conditions along the $K_d \times$ SD continuum (Fig. 1). During the preimpoundment years, $K_d \times$ SD values of Wood Lake were ~2.18, and they rose during the postimpoundment years to 2.89, i.e. the movement of $K_d \times$ SD values on the continuum was opposite that of Southern Indian Lake. We would predict that yellow color (organic stain) controls the light regime of Wood Lake—a condition not shared by the clear-water Southern Indian Lake. Comparisons between the two systems, used to assess the degree of change in optical conditions caused by the impoundment at Southern Indian Lake, should have considered the effects of both color and turbidity on light regimes, as suggested by the $K_d \times$ SD continuum (Fig. 1). Thus, combining the SD depth with SP readings imparts additional information about the loading of PAR-modifying constituents in natural waters not interpretable with either instrument alone.

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