Hydrobiologia **468:** 213–232, 2002.

Tripton, transparency and light penetration in seven New York reservoirs *

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Received 6 March 2001; in revised form 16 October 2001; accepted 19 November 2001

Key words: optics, attenuation coefficient, Secchi disc, turbidity, clay, reservoirs

Abstract

Temporal patterns and inter-system differences in the attenuation coefficient for scalar irradiance (K_s), Secchi disc transparency (SD), several measures of tripton, and chlorophyll *a* (Chl) are documented for the lacustrine zones of seven reservoirs (nine distinct basins) in New York (U.S.A.), based on a single year of comprehensive measurements. Analyses of these data and historic (12 years) observations of SD and Chl, including application of empirical and deterministic modeling frameworks, demonstrate that inorganic tripton is the primary attenuating constituent responsible for the substantial differences in K_s and SD among these basins, and the major temporal variations observed in these optical characteristics in most of the study basins. These inorganic particles, of terrigenous origins, are supplied directly to the water column of these basins in inflows, particularly during runoff events, and through the sediment resuspension process. Comparison of the measures of tripton indicates electron-microscopy-based measurements performed somewhat better than gravimetric analyses in explaining the variations in K_s and SD in the lower concentration systems. Increases in average SD values by factors of 2–5, compared to prevailing values, are predicted for the study basins with the deterministic model for the case of no tripton.

Introduction

The behavior of light in water, particularly its attenuation with depth, has important ecological and water quality implications. The extent of light penetration can be an important regulator of features of density stratification (Effler & Owens, 1985), and it establishes the vertical limit of primary production (e.g. photic zone; Vollenweider, 1974). The intensity of attenuation processes is widely quantified by diffuse light attenuation coefficients (K_x, m^{-1}), based on measurements of irradiance with depth (Kirk, 1994). The visibility of submerged objects, as commonly measured with a Secchi disc (SD, m), is also regulated by attenuating processes (Tyler, 1968; Preisendorfer, 1986). Though K_x and SD respond differently to the attenuating processes of absorption and scattering (Effler, 1985; Kirk, 1994), and therefore changes in concentrations of attenuating constituents, the distributions of these two variables are often correlated (Wetzel, 1983).

Light attenuation is regulated by the composition and concentration of various attenuating constituents (Kirk, 1994), which include water itself, gelbstoff, phytoplankton, and tripton (Weidemann & Bannister, 1986; Kirk, 1994). Particulate constituents regulate light attenuation in the vast majority of inland waters (Davies-Colley & Smith, 2001). Differences in concentrations of these constituents are responsible for the wide inter-system differences and dynamics within in-

* Contribution No. 203 of the Upstate Freshwater Institute.

dividual systems reported for both K_x and SD (Wetzel, 1983; Cole, 1994). Resolution of the constituent(s) regulating K_x and SD is fundamental ecological and water quality information because of the important influence of these characteristics on aquatic ecosystems (Kirk, 1994) and the public's perception of water quality (Shapiro, 1975; Effler, 1985). Phytoplankton biomass, as represented by the concentration of chlorophyll *a* (Chl, μg l^{-1}), has received much attention as an important attenuating constituent, and regulates the dynamics of these variables in many productive inland waters (e.g. Jewson, 1977; Megard et al., 1971, 1980; Field & Effler, 1983; Tilzer, 1983; Oliver & Ganf, 1988). Reduction in external nutrient loading, to reduce Chl levels has been a widely applied management approach to achieve increased light penetration and SD levels (Cooke et al., 1993). However, increasingly systems are being identified where tripton is important or dominant in regulating these optical characteristics. This material can be produced internally by chemical precipitation (e.g. $CaCO_3$ in hardwater systems; Weidemann et al., 1985; Effler et al., 1987, 1991; Effler, 1996), supplied as terrigenous inputs (Kirk, 1985; Effler et al., 2000), or resuspended from bottom sediment (Phlips et al., 1995; Effler et al., 1998a,b). Regulation of K_x and SD by tripton in optically impacted systems may require management approaches other than reduction of nutrient loads.

Evidence for the importance of tripton has been both indirect/circumstantial (e.g. failure of Chl as a predictor) and direct, based on paired observations of optical properties that include tripton. Appropriate measurements to represent the effects of tripton on light attenuation remain problematic because of analytical limitations, the disconnect between mass concentration measures of particulates and their optical impacts (Owen, 1974; Treweek and Morgan, 1980; Kirk, 1994), and the lack of information concerning chemical composition (e.g. resolution of components and origins). Measurements of total suspended solids (TSS, mg l^{-1}) and the non-volatile (or fixed) fraction (FSS, mg l^{-1}) have been used to represent the effects of tripton in several instances (Geddes, 1984; Limon et al., 1989; Phlips et al., 1995; Knowlton & Jones, 2000). For example, Phlips et al. (1995) estimated the concentration of tripton in Lake Okeechobee as the residual of TSS and the estimated suspended solids concentration of phytoplankton, calculated from Chl assuming the stoichiometry of phytoplankton to be TSS:Chl=100 (Reynolds, 1984). Knowlton & Jones (2000) estimated tripton (non-algal seston) in several Missouri reservoirs as the summation of FSS from analyses with glass fiber filters (effective pore size of 1.2 μm) and TSS from this filtrate collected on membrane filters (pore size of 0.45 μm). Measurements of particle surface area per unit volume (e.g. scanning electron microscopy) represents a conceptual advancement over mass concentrations, as optical impacts of this material are inherently related to its surface area, not its mass (Owen, 1974; Treweek and Morgan, 1980). Further, when x-ray energy spectroscopy is coupled to scanning electron microscopy (e.g. Johnson et al., 1991), this individual particle analysis methodology supports chemical partitioning of the particle population that can lead to resolution of the origins of the tripton (Yin & Johnson, 1984; Johnson et al., 1991; Effler et al., 2000).

This paper documents temporal patterns and inter-system differences in K_x, SD, several measures of tripton, and Chl for seven reservoirs. The role of tripton in regulating K_x and SD dynamics within individual systems, and differences in these optical characteristics among the test systems, is evaluated using empirical and deterministic model frameworks. The performances of gravimetric and scanning electron microscopy-based measures in representing the impact of tripton on these optical characteristics are compared.

Study systems

Description/setting

The seven reservoirs included in this study are located in southeastern New York; moving west to east, they are Cannonsville, Pepacton, Neversink, Rondout, Schoharie, Ashokan and West Branch (Fig. 1). These reservoirs provide $\geq$85% of the water supplied to New York City. The four western reservoirs comprise the Delaware system. The Catskill system includes Schoharie and Ashokan. The Delaware system drains an area $\sim$2570 km^2; the Catskill system has a watershed area of $\sim$1440 km^2. The upstream reservoirs in the Delaware system (Cannonsville, Pepacton and Neversink) are used to augment flow in the Delaware River during low flow periods, as well as provide water for the water supply (withdrawals usually from stratified depths). Rondout, West Branch and Ashokan are downstream reservoirs, in that a large percentage of the inflow received is from an upstream reservoir(s). Rondout Reservoir receives >80% of its inflow from

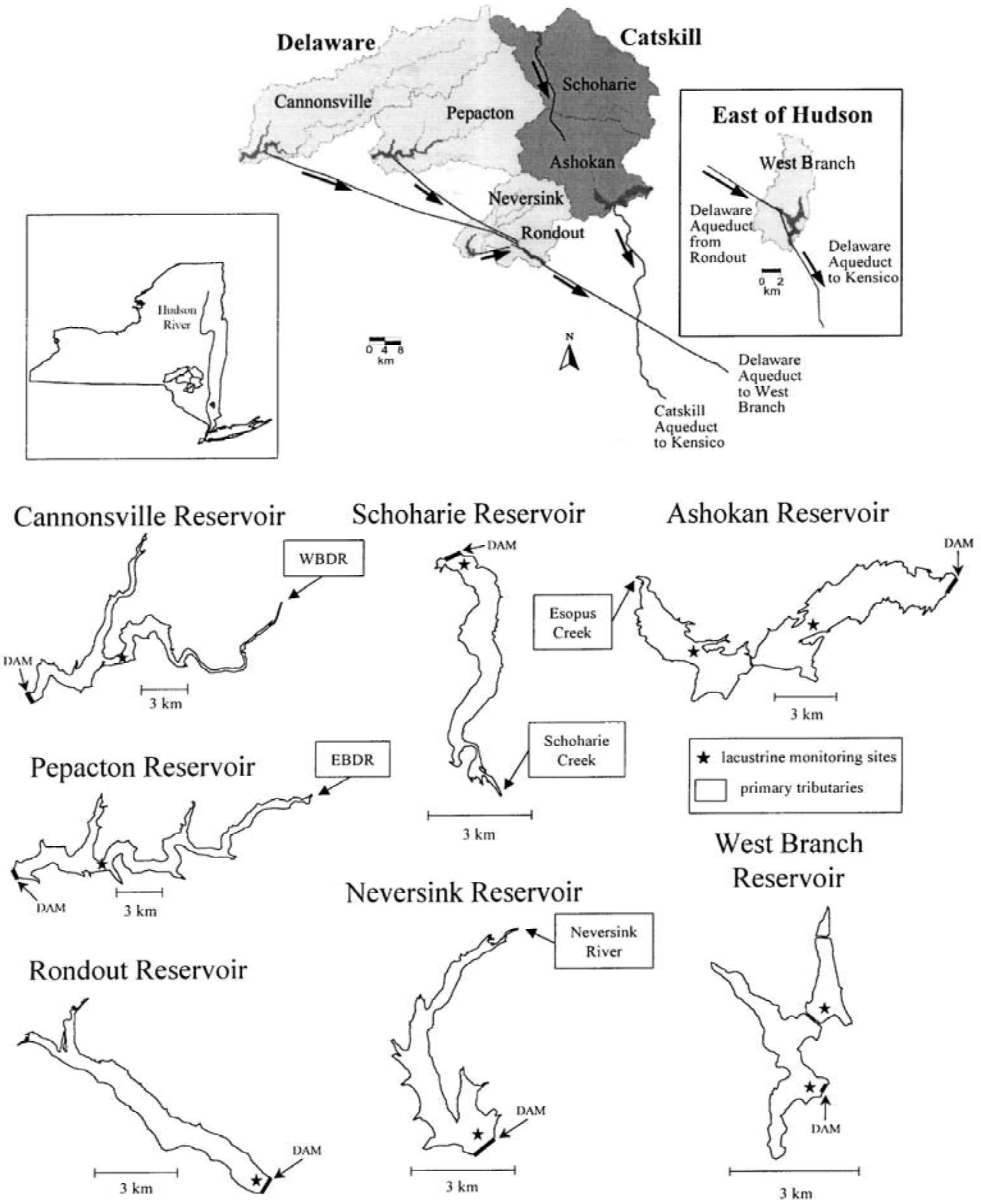

Figure 1. Study reservoirs (7) with lacustrine monitoring sites and primary tributaries (WBDR – West Branch of Delaware River, EBDR – East Branch of Delaware River) identified. Delaware and Catskill systems with aqueducts. Position of watersheds within New York.

the three upstream reservoirs of the Delaware System. The south basin of West Branch Reservoir is generally considered to be part of the Delaware System because it receives its inflow from Rondout Reservoir (via a tunnel; Fig. 1). Effects of inputs from the small local watershed (107 km^2) of West Branch Reservoir are largely isolated in its north basin (e.g. Effler et al. 2001b). Outflow from Schoharie Reservoir reaches the west basin of Ashokan Reservoir via a natural tributary (Fig. 1); flow from this upstream reservoir represents ~35% on average of the total inflow to the west basin. Export from the west basin to the east basin of Ashokan Reservoir is controlled by operating procedures.

These reservoirs represent a rather wide range of morphometries, flushing rates, operating conditions

Table 1. Physical/hydrologic characteristics for study reservoirs

Reservoir	Latitutde	Longitude	Volume[a] ($\times 10^6$ m^3)	Surface[a] area (km^2)	Mean[a] depth (m)	Max.[a] depth (m)	Drawdown[b] (m)	Flushing [c] rate (yr^{-1})	Watershed area (km^2)	Ratio[d]
Cannonsville	42° 02′ 46″	75° 22′ 24″	363	19.3	19	50	15.9/19.6	2.6	1160	60
Pepacton	42° 04′ 38″	74° 58′ 04″	538	19.9	27	53	13.9/15.6	1.6	939	47
Neversink	41° 49′ 30″	74° 38′ 30″	134	5.4	25	49	18.0/17.3	2.4	233	43
Rondout	41° 48′ 03″	74° 25′ 33″	200	8.2	24	52	10.8/2.3	6.8	239	29
Schoharie	42° 23′ 29″	74° 27′ 05″	79	4.0	17	40	17.4/14.7	10.1	815	204
Ashokan									630	55
West basin	41° 56′ 17″	74° 13′ 10″	174	11.5	15	47	9.7/7.3	5.4	–	–
East basin	41° 56′ 17″	74° 13′ 10″	299	20.0	15	26	8.6/6.3	3.1	–	–
West Branch	41° 24′ 12″	73° 41′ 45″	35	3.9	9	15	3.9/2.2	22.8	48	12

[a]Full reservoir values.
[b]Mean of maximum drawdown observed annually/actual maximum drawdown over study period.
[c]Annual average rate.
[d]Watershed area/reservoir area.

and relative watershed size (Table 1). Five of the reservoirs have maximum depths >45 m. The volumes of the reservoirs generally vary seasonally associated with export of water consistent with their function and operation. This is manifested in the 'drawdown' of the water surface of the reservoirs. Drawdown occurs to a greater extent in the upstream reservoirs; e.g. Rondout and West Branch remain relatively full in most years. Major interannual variations in drawdown (and flushing rate) occur in the upstream impoundments associated with natural variations in runoff (e.g. Owens et al., 1998). Generally, drawdown proceeds over the mid-summer to fall (e.g. maximum) interval (Owens et al., 1998). The drawdown encountered during the study year(s) for the various reservoirs did not deviate greatly from the long-term averages, indicating hydrologic and related operating conditions were generally typical. The average flushing rate of the study basins ranges from 1.6 (Pepacton) to 22.8 yr^{-1} (West Branch). The ratio of the watershed area to reservoir surface area is much greater for Schoharie Reservoir than the other study systems (204).

Water column particles

Peng et al. (2001) characterized the particle assemblage of the upper waters of six of the reservoirs (exclusive of Cannonsville, more limited measurements of this reservoir by Effler et al., 1998b) with scanning electron microscopy equipped with automated image analysis and x-ray energy spectroscopy (SAX). These analyses provided both geometric and chemical (elemental) characterizations of particles > 0.3 μm diameter. Results in terms of particle cross-sectional area per unit volume (PAV; cm^2 1^{-1}) were partitioned according to contributions from seven generic particle types: clay minerals (Clay), iron and manganese rich (Fe–Mn), silica rich (Si-rich), quartz (Qtz), 'Other', diatoms (Diatom) and the No/Low (N/L; Table 2) x-ray (e.g. organic particles) group (Peng et al., 2001). The summation of the first five groups represents the PAV of inorganic tripton (PAV$_i$); essentially all these particle types have terrigenous origins in these systems (Peng et al., 2001). SAX is less quantitative for organic particles. Details of the SAX methodology and the development of criteria for the chemical classes from the x-ray signal are described elsewhere (Yin & Johnson, 1984; Johnson et al., 1991).

A selective summary of this earlier work (Effler et al., 1998b; Peng et al., 2001) is presented here (Table 2) to support subsequent analyses of related optical impacts. Wide variations in PAV$_i$ were observed in each of the nine basins (CV $\geq$0.5), and particularly high average values were observed for Cannonsville, Schoharie and the west basin of Ashokan. Though PAV values for the No/Low x-ray grouping are more uncertain than for the inorganic particle groups (Johnson et al., 1991; Peng et al., 2001), the available data indicate contributions of organic particles from other than diatoms (other phytoplankton plus detritus) were low. Inorganic tripton dominated PAV in all of the reservoirs. Clay minerals were the single largest component of PAV, in all the basins, except Rondout Reservoir. Diatoms made a particularly large contribu-

Table 2. Summary of PAV measurements for seven New York reservoirs (Effler et al., 1998a; Peng et al., 2001)

Reservoir	Year	*n*	[b]PAV_i (cm^2 l^{-1})			Avg. Contributions (%)						
			x̄	CV[a]	range	N/L	Clay	Fe-Mn	Si-rich	Qtz	Diatom	Other
Cannonsville[c]	1995	13	5.2	0.5	1.5–9.6	–	66.4	–	–	–	–	–
Pepacton	1997	30	1.4	0.7	0.3–5.2	1.8	48.9	3.4	7.9	14.4	14.8	8.7
Neversink	1998	18	1.6	0.7	0.4–4.5	4.3	47.4	3.7	5.2	15.1	4.7	19.6
Rondout	1997	30	0.9	1.0	0.2–3.4	1.6	24.5	4.1	7.4	15.9	39.8	6.8
Schoharie	1998	16	9.3	0.7	1.1–21.6	0.5	64.3	3.3	8.3	14.5	0.7	8.4
Ashokan	1997											
West		28	4.4	1.1	0.7–21.3	0.5	57.7	3.0	8.8	19.2	3.5	7.3
East		29	1.8	0.6	0.4–7.2	1.8	42.3	3.4	9.8	19.8	14.5	8.4
West Branch	1998											
South[a]		18	1.6	0.8	0.5–6.4	4.7	38.1	7.4	10.5	12.5	11.1	15.7
North[a]		18	2.2	0.9	0.4–6.4	3.8	28.4	5.2	14.7	11.5	20.3	16.1

[a]CV – coeficient of variation.
[b]PAV_i equals the summation of contributions to PAV from Clay, Fe-Mn, Si-rich, Qtz, and Other groups.
[c]Particle classification scheme used (Effler et al., 1998a) differed from Peng et al. (2001), but clay fraction can be compared.

tion in Rondout Reservoir (~40%), in part because the total PAV and PAV_i values that prevailed in this downstream basin were low. Variations in PAV_i were driven by variations in the clay mineral fraction (PAV_{cl}) in all of the basins ($R^2 \geq 0.94$), establishing regulation by terrigenous inputs (Effler et al., 2000).

Methods

Measurements

Methods for the Cannonsville Reservoir field and laboratory measurements (1995) were described previously (Effler et al., 1998b). Sampling and field measurements were conducted over the April–November interval at a lacustrine site in each study basin (Fig. 1) for a single year. Pepacton, Rondout and Ashokan were monitored weekly in 1997. Neversink, Schoharie and West Branch were monitored bi-weekly in 1998. Cannonsville was monitored weekly in 1995, but SAX analyses were conducted on only a subset of samples for this impoundment.

Secchi disc transparency was measured with a 20 cm diameter black and white quadrant disc. Underwater scalar irradiance measurements for the photosynthetically active radiation (PAR) wavelength interval (400–700 nm) were made using a spherical (scalar) sensor (LI-COR 193SB), powered by a Seabird Sealogger Profiler (Model SDE 25; Sea-Bird Electronics, Inc., Bellevue, Washington, U.S.A.). Readings were recorded at a rate of 8 s^{-1}, with an instrument descent rate of ~1.2 m s^{-1}. Irradiance readings were made to below the 10% light level ($Z_{0.1}$), and usually to about the 1% ($Z_{0.01}$) level. The vertical attenuation coefficient (henceforth K_s, instead of K_x) was calculated according to Beer's Law, at depths bounding $Z_{0.1}$. Vertical attenuation coefficients determined by cosine [both up (K_u) and downwelling (K_d)] and scalar PAR sensors at $Z_{0.1}$ are nearly equivalent (Weidemann & Bannister, 1986; Kirk, 1994; Effler et al., 1998b). Paired determinations made on certain days supported this near equivalence for these reservoirs.

Chlorophyll *a* (Chl, μg l^{-1}) was determined according to the method of Parsons et al. (1984). Analyses (gravimetric) of TSS and FSS were conducted according to standard methods (Am. Public Health Assoc., 1992). The concentration of tripton (Tr, mg l^{-1}) was estimated according to the protocol of Phlips et al. (1995; Tr = TSS − (100·Chl). Measurements used in this analysis are based on samples collected from the near-surface layer. Secchi disc and Chl data collected as part of New York City's long-term monitoring program (1988–1999; e.g. NYCDEP 1993) have been used to support this analysis. The Chl values from the long-term program reflect depth-integrated samples (~ photic zone). These have been found to usually correspond closely to near-surface values (e.g. Doerr et al., 1998).

Auxiliary data on tributary flow rates and the water surface elevation (WSE) of the reservoir basins for the study intervals were obtained from the United States Geological Survey (USGS) and the New York City Department of Environmental Protection (NYCDEP), respectively. Relationships of TSS concentration as a function of flow were developed for each of the five primary tributaries in this system of reservoirs (Fig. 1), based on measurements made by NYCDEP (unpublished data) as part of its long-term monitoring program. The relationships reflect the slopes of least squares regression analyses and the range of flows over which TSS measurements were made.

Models: empirical and deterministic

The dependencies of K_s and SD on Chl were evaluated according to the following widely applied empirical frameworks (Jewson, 1977; Megard et al., 1979, 1980; Field & Effler, 1983; Tilzer, 1983; Effler, 1996)

$$K_s = (k_c \cdot \mathrm{Chl}) + k_w \quad (1)$$

$$1/\mathrm{SD} = (k'_c \cdot \mathrm{Chl}) + k'_w \quad (2)$$

where k_c and k_w are constants determined from linear regression of K_s on Chl, and $k_c{}'$ and $k_w{}'$ are constants determined from linear regression of 1/SD on Chl. The coefficients k_c and $k_c{}'$ have units of m^2 mg^{-1} Chl, and k_w and $k_w{}'$ have units of m^{-1}. The form of these expressions has been described as partitioning the contributions of phytoplankton (e.g. k_c·Chl) *versus* non-phytoplankton (e.g. k_w) components (Bannister, 1974; Megard et al., 1979).

The dependence of K_s and SD on tripton was evaluated for four different measures of this population of non-phytoplankton particles, PAV_i, PAV_{cl}, Tr, and FSS. Only Tr is expected to include organic detritus. PAV_i and FSS are particle surface area and gravimetric representations, respectively, of the inorganic component of tripton in these systems. PAV_{cl} is the regulating component of PAV_i dynamics in these systems (Peng et al., 2001). Corollary empirical frameworks to those used to evaluate the dependence of K_s and SD on Chl (Equations (1) and (2)) have been adopted to investigate the dependence of these optical characteristics on tripton, as illustrated for Tr below

$$K_s = (k_{Tr} \cdot \mathrm{Tr}) + k_y \quad (3)$$

$$1/\mathrm{SD} = (k'_{Tr} \cdot \mathrm{Tr}) + k'_y \quad (4)$$

where k_{Tr} and k_y are constants determined from linear regression of K_s on Tr, and $k_{Tr}{}'$ and $k_y{}'$ are constants determined from linear regression of 1/SD on Tr. The performance of these empirical models is evaluated using the adjusted coefficient of determination and significance of the slope coefficient. The adjusted R^2 ($R^2{}_{adj}$) was utilized because it removes the impact of degrees of freedom and gives a quantity that is more comparable than R^2 for models involving different numbers of parameters (Rawlings et al., 1998). Tests for significance of slope coefficients were performed at a commonly used level of significance (α = 0.05) and at α = 0.001. The more stringent significance level (α = 0.001) was used to keep the probability of committing a Type I error in any of the 108 regressions at an acceptable level (∼10%).

A deterministic probabilistic model for SD that resolves the effects of several light attenuating constituents, including phytoplankton and tripton, developed and tested by Effler et al. (2001a), was also applied to resolve the role tripton played in regulating the population of SD observations for the study basins. The framework is deterministic in that it accommodates the dependence of SD on the processes of absorption and scattering, as quantified by corresponding coefficients (a and b, respectively; m^{-1}), and the contributions of various attenuating constituents to these processes (as simple summations, Fig. 2a). The complexities of spectral variations in a and b (Kirk, 1994) are simplified by considering spectral average values for the PAR interval (e.g. Weidemann & Bannister, 1986; Oliver & Ganf 1988; Effler et al., 2001a). Values of SD are calculated from a and b according to contrast transmittance theory (Tyler, 1968; Preisendorfer, 1986; Fig. 2a)

$$\mathrm{SD} = \Gamma \cdot (K_d + c)^{-1} \quad (5)$$

where K_d = attenuation coefficient for down-welling irradiance (m^{-1}), c = beam attenuation coefficient (m^{-1}), and Γ = constant (dimensionless). Both K_d (Kirk, 1981) and c, and thus SD (Equation (5)), can be expressed in terms of a and b (Fig. 2a).

The framework accommodates factors that contribute to variations in SD measurements through Monte Carlo calculations (Fig. 2b; Effler et al., 2001a). The sources of variability accommodated include (Fig. 2b): (1) reasonable variations in model coefficients, as described in the scientific literature, that describe variations in the absorption and scattering characteristics of the phytoplankton community associated with shifts in composition (K_a and K_b, Fig. 2; Weidemann & Bannister, 1986) and the effects of variable ambient conditions during SD measurements (Γ, Fig. 2b; Preisendorfer, 1986), and (2) reasonable variations in certain attenuating components, centered around

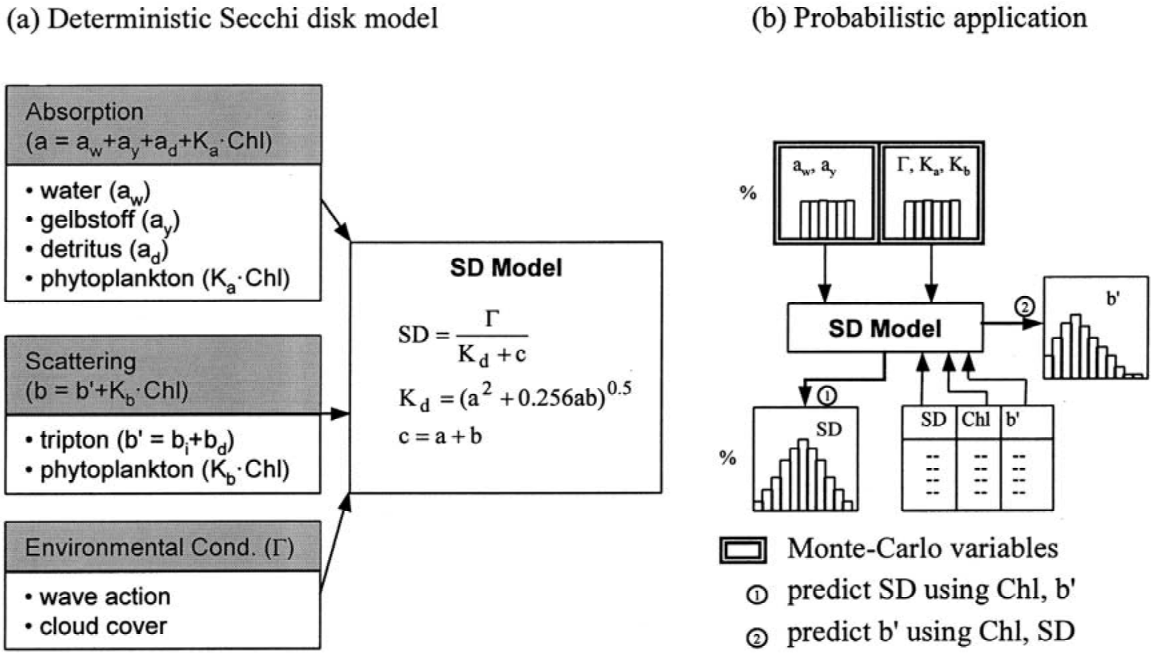

Figure 2. Deterministic probabilistic Secchi disc (SD) model: (a) Secchi disc optics model, and (b) strategy for Monte Carlo calculations to support probabilistic predictions of SD (from Effler et al., 2001a).

Table 3. Inputs for Secchi disc transparency model for New York reservoirs (modified from Effler et al., 2001a)

Model/Input	Values	Source(s)
General		
K_a (m^2 mg Chl^{-1})	0.012–0.022	Bannister & Weidemann (1984)
K_b (m^2 mg Chl^{-1})	0.05–0.15	Weidemann & Bannister (1986)
		Effler & Perkins (1996)
Γ (dimensionless)	7.9–9.6	Preisendorfer (1986)
Site specific		
a_w	0.015–0.20	Effler et al. (1998b)
a_y	0.04-0.13	Effler et al. (1998b)

the limited system-specific determinations (a_w and a_y, Fig. 2, Table 3). This modeling framework can be used to predict SD from paired values of Chl and tripton scattering (b', Fig. 2a), or b' from paired measurements of SD and Chl (Fig. 2b). Distributions have been formed for model inputs (Fig. 2b, Table 3; Effler et al., 2001a) to define the important sources of variability to support probabilistic (e.g. as distributions) predictions. Values are drawn randomly from these specified distributions in the Monte Carlo calculations with the deterministic model (Fig. 2b). One thousand calculations were performed for each set of observations based on random selections from the Monte Carlo variables (Effler et al., 2001a). The model was applied here to: (1) simulate the distribution of SD values that would prevail in each study system in the absence of tripton (i.e. $b' = 0$), and (2) estimate the magnitudes of b' for the various basins, and thereby evaluate its relationship to an independent measure of tripton.

Results and discussion

Multiple reservoir analyses

Rather broad ranges of average values of Chl, measures of tripton, SD and K_s were represented by the conditions documented here for the nine reservoir basins for the study interval (Fig. 3). Average Chl concentrations ranged from ~2 μg l^{-1} for Schoharie Reservoir to ~9 μg l^{-1} for Cannonsville Reservoir (Fig. 3a). A similar range of average Chl values was observed for the subset of the Delaware system reservoirs. The range of average Chl values was much narrower for the three Catskill basins, ~2–3.9 μg l^{-1} (Fig. 3a). The average Chl concentration for the north

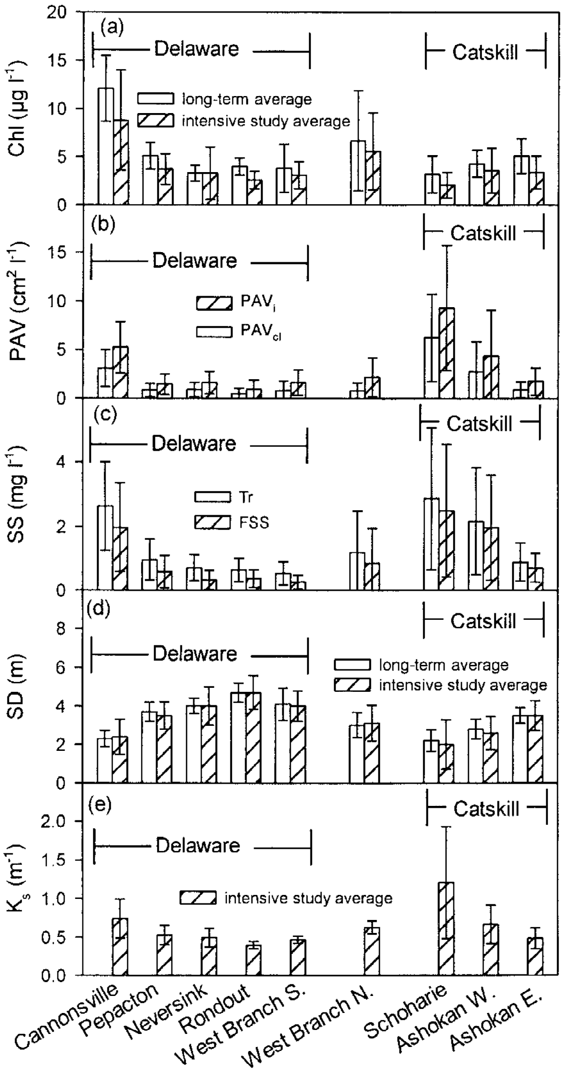

Figure 3. Rankings of average conditions for the nine study basins: (a) average Chl for intensive study year and average Chl for 12 years (1988–1999), (b) average PAV_i and PAV_{Cl} for intensive study year, (c) average Tr and FSS for intensive study year, (d) average SD for intensive study year and average SD for 12 years (1988–1999), and (e) average K_S for intensive study year. Vertical bars with dimensions of ± 1 standard deviation.

basin of West Branch Reservoir (5.9 μg l^{-1}) was the second highest of all the study basins. The rankings for measures of tripton (Fig. 3b, c) were quite different from Chl (Fig. 3a); the three highest averages, in descending order, were for Schoharie, Cannonsville, and the west basin of Ashokan. The rankings for average SD and K_S were consistent with each other (Fig. 3d, e); e.g. the lowest SD and highest K_S were observed for Schoharie Reservoir, the highest SD and lowest K_S were measured in Rondout Reservoir. These rankings (Fig. 3d, c) tracked rather closely those observed for measures of tripton (Fig. 3b, c), but were dissimilar from the Chl ranking (Fig. 3a). The vertical limits of the photic zone, corresponding to the study average K_S values, ranged from 3.8 m (Schoharie) to 11.7 m (Rondout).

Differences in phytoplankton biomass, as measured by Chl, did not explain the rather substantial differences for both SD and K_S reported among these nine basins (Fig. 4a, b). The counter-intuitive relationship for the three Catskill basins, decreasing light penetration with decreases in Chl, was largely an artifact of the inclusion of the conditions of Schoharie Reservoir (Fig. 4a, b). High inorganic tripton levels may contribute to low Chl concentrations in certain of the study basins (e.g. Schoharie) in at least two ways: (1) by limiting the light available to support phytoplankton growth (e.g. Lind et al., 1992; Phlips et al., 1995), and (2) by providing large quantities of surface area of clay minerals (Table 2) that is known to have high affinity for phosphate (e.g. competes with phytoplankton; Edzwald et al., 1976; Mayer et al., 1987). Positive relationships are observed between Chl and 1/SD and K_S among the Delaware system basins (Fig. 4a, b). The conditions in the north basin of West Branch Reservoir fit the Delaware system relationship well (Fig. 4a, b).

The differences in SD and K_S among all the basins were instead largely explained by differences in levels of tripton (Fig. 4c–j), though these populations of average observations were not evenly distributed (conditions of Schoharie are heavily weighted). The strongest relationships were observed for PAV_i (Fig. 4c, d) and PAV_{Cl} (Fig. 4e, f); those for Tr (Fig. 4g, h) and FSS (Fig. 4i, j) were weaker. Clearly, the major differences in SD and K_S reported for the three Catskill basins were primarily a result of differences in the levels of inorganic tripton, specifically the level of clay minerals (Fig. 4c–f). The differences in the Delaware system basins, were associated primarily with Cannonsville Reservoir (Fig. 4c–j). Higher levels of both Chl and tripton contributed to the lower SD and higher K_S observed in Cannonsville Reservoir compared to the other Delaware system basins. Decreases in tripton levels, and the associated increases in light penetration and clarity, in downstream basins in both the Delaware and Catskill systems (Fig. 3) in part reflects the benefits of deposition of this material in the upstream basins. Progressive decreases in the downward flux (deposition) of tripton were docu-

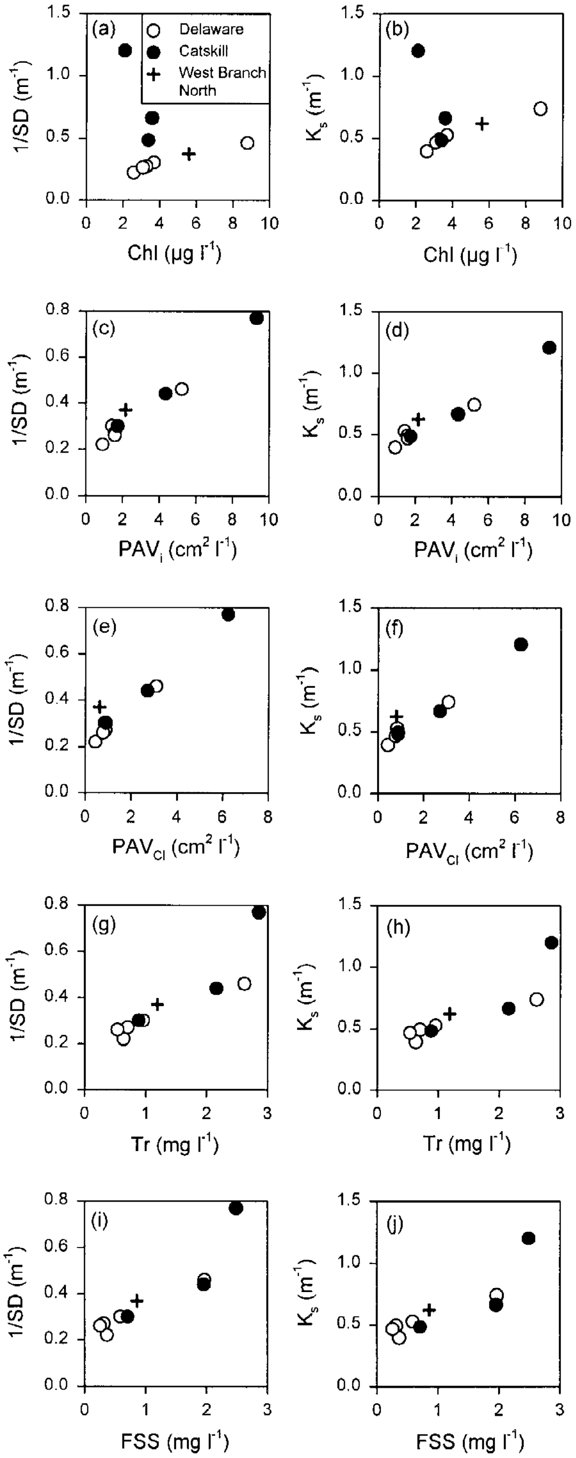

Figure 4. Analysis of roles of light attenuating constituents in regulating differences in study average conditions for optical characteristics across nine reservoir basins: (a) 1/SD vs. Chl, (b) K_S vs. Chl, (c) 1/SD vs. PAV_i, (d) K_S vs. PAV_i, (e) 1/SD vs. PAV_{Cl} (f) K_S vs. PAV_{Cl}, (g) 1/SD vs. Tr, (h) K_S vs. Tr, (i) 1/SD vs. FSS, and (j) K_S vs. FSS.

mented from the upstream to downstream basins over the study period (Effler et al., 2001b).

The 12 year data base of paired SD and ChI measurements from New York City's long-term monitoring program supports the general representativeness of the findings from the more comprehensive, but shorter-term, measurements (Fig. 3a, d). The long-term average values and the rankings among the study basins were generally similar to those reported for the more comprehensive study year (i.e. decoupling in rankings for Chl and SD), though substantial interannual variations have been observed in certain of the basins (Fig. 3a, d). Interannual variations in average Chl and SD (as 1/SD) within the 12 year record were found to be largely uncoupled ($R^2 \leq 0.25$) for six of the nine study basins. Only the relationships for Cannonsville Reservoir (R^2=0.66), and the north (R^2 = 0.38) and south (R^2 = 0.59) basins of West Branch Reservoir were significant. However, each of these relationships depended greatly on a single pair of observations. The character of the record is generally consistent with the position (Figs 3 and 4) that inorganic tripton is more important than phytoplankton biomass in causing the observed differences in SD and light penetration between these reservoirs.

Detailed time-series

Detailed time-series of the measures of light attenuating substances, flow in the primary tributary, WSE, SD, and K_S are presented here for two of the study basins, Neversink (Fig. 5) and Schoharie (Fig. 6) reservoirs, as examples of the character of dynamics and to identify potential forcing conditions. Average values of SD and K_S for these two systems for the study interval bound most of the conditions observed for the study basins (Fig. 3). Temporal patterns of inflow and drawdown are included because of related inputs of tripton to the water columns of the systems. Most of these reservoirs, but particularly the upstream basins, receive high loads of terrigenous sediment, especially during runoff events (e.g. Longabucco & Rafferty, 1998). This has been attributed in part to the highly erodable character of the soils in these watersheds (Bader, 1990). Suspended solids concentrations increase in the primary tributaries as flow increases (Fig. 7). The highest tributary concentrations occur in the Catskill system (Fig. 7). These inflow conditions undoubtedly promote the higher tripton levels observed in these basins (Fig. 3b, c). Further, evidence has been presented that the seasonal drawdown

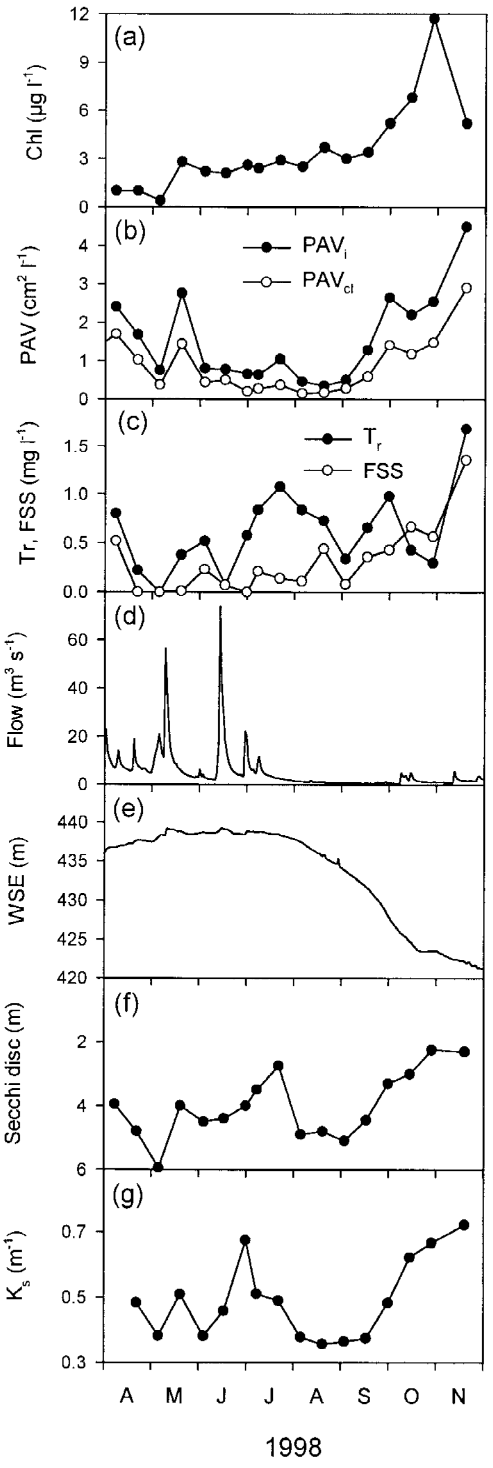

Figure 5. Time-series for Neversink Reservoir for the April–November interval of 1998: (a) Chl in the near-surface layer, (b) PAV_i and PAV_{Cl}, in the near-surface layer, (c) Tr and FSS in the near-surface layer, (d) daily average flow in Neversink River, (e) daily average water surface elevation (WSE), (f) SD, and (g) K_S.

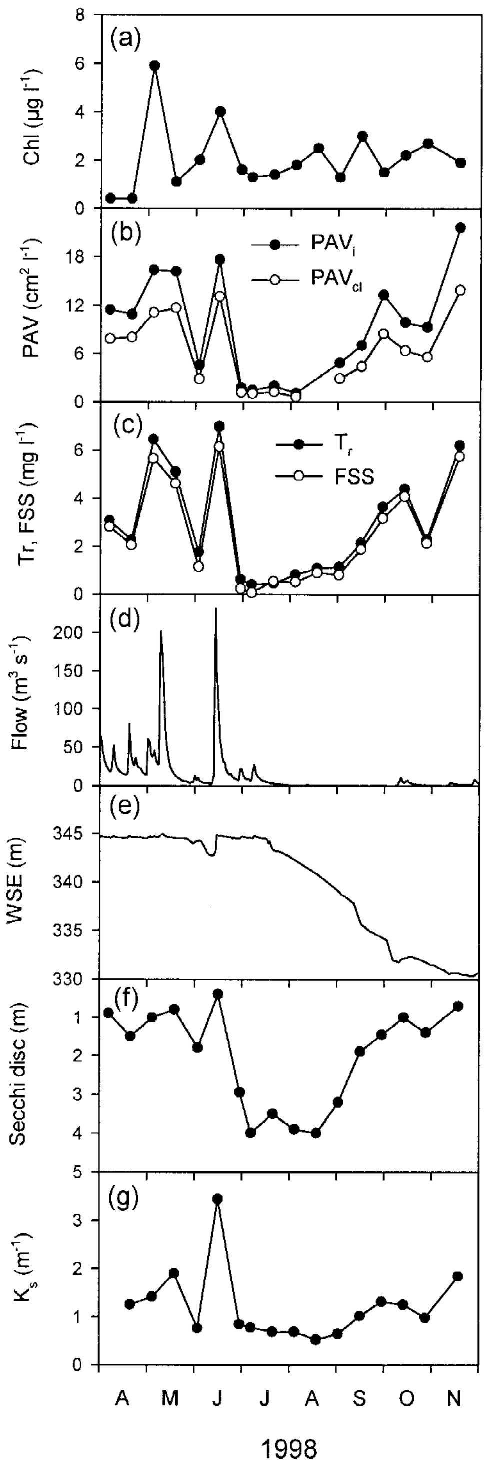

Figure 6. Time-series for Schoharie Reservoir for the April–November interval of 1998: (a) Chl in the near-surface layer, (b) PAV_i and PAV_{Cl} in the near-surface layer, (c) Tr and FSS in the near-surface layer, (d) daily average flow in Neversink River, (e) daily average water surface elevation (WSE), (f) SD, and (g) K_S.

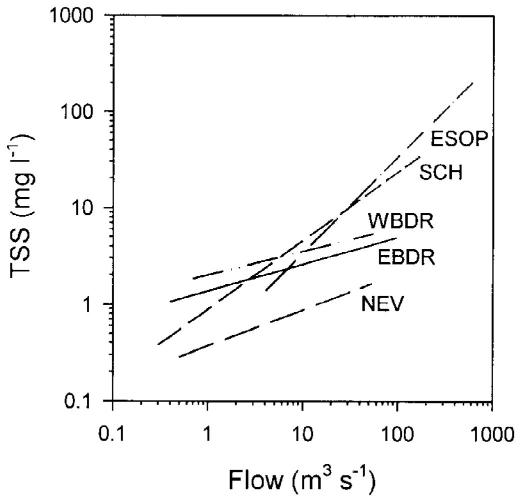

Figure 7. Total suspended solids (TSS) concentration – flow relationships for five reservoir tributaries, from linear least squares regression analysis (ESOP – Esopus Creek, SCH – Schoharie Creek, WBDR – West Branch of the Delaware River, EBDR – East Branch of the Delaware River, NEV – Neversink River).

Table 4. Relationships between Secchi disc transparency (SD) and vertical attenuation coefficient (K_s) for study basins

Reservoir	1/SD *versus* K_s		SD·K_s	
	n	R^2	$\bar{x}$	cv
Cannonsville	26	0.64	1.62	0.20
Pepacton	26	0.67	1.69	0.13
Neversink	16	0.62	1.87	0.18
Rondout	24	0.04	1.92	0.19
WestBranch S.	15	0.05	1.94	0.17
WestBranch N.	13	0.62	2.00	0.16
Schoharie	16	0.96	1.87	0.29
Ashokan W.	24	0.90	1.59	0.18
Ashokan E.	21	0.66	1.67	0.17

of most of these basins (Table 1) promotes sediment resuspension in shallow areas (Effler et al., 1998a,b, 2001b), by exposing shoreline that was previously below the influence of wave-induced mixing to this turbulence as drawdown proceeds. While substantially different features were observed in the detailed patterns of attenuating substances, SD, and K_s in the various basins, certain characteristics appear to have been broadly occurring, as depicted in these two selected time-series (Figs 5 and 6).

Concentrations of Chl remained less than 5 μg l^{-1} in Neversink Reservoir through mid-September of 1998, followed by the development of a distinct peak of $\sim$ 12 μg l^{-1} in late October (Fig. 5a). Levels of PAV_i and PAV_{CL} were high during spring turnover (elevated turbulence, through mid-April), mid-May, and during the fall mixing interval (Fig. 5b). Certain features of the patterns of the other measures of tripton, Tr and FSS, were similar to those of PAV_i, such as the decreases in April and increases in November (Fig. 5c). However, substantial differences were observed, particularly for Tr during summer, and on two dates in fall estimates of Tr were less than FSS (i.e. inconsistent; Fig. 5c). Runoff events occurred in Neversink River, the primary tributary for the reservoir ($\sim$ 80% of the total inflow), in late March/early April, in mid-May and mid-June (Fig. 5d). The temporal patterns of the measures of tripton in the reservoir in April and May are consistent with inputs from this tributary, however, similar response to the June runoff event was not evident (Fig. 5b–d). The surface of Neversink Reservoir was drawdown progressively from July through the end of the monitoring period; the WSE dropped $\sim$ 20 m over this interval (Fig. 5e). The progressive increases in three of the four measures of tripton (PAV_i, PAV_{Cl}, FSS) over this interval (Fig. 5b, c), in the absence of runoff events (Fig. 5d), indicates the occurrence of internal loading of tripton associated with the process of sediment resuspension. Resuspension was promoted by at least two factors during that interval, drawdown (e.g. Effler et al., 1998a, 2001b) and the increased watercolumn turbulence that attends the fall mixing period (Jassby & Powell, 1975; Wodka et al., 1983). Resuspension has been observed to occur in a number of lakes and reservoirs during turnover (Bloesch, 1995).

Similar temporal patterns were observed for SD (Fig. 5f) and K_s (Fig. 5g) in Neversink Reservoir, except in late June and July. SD increased to the study maximum and K_s decreased in early May, coincident with decreases in tripton levels (Fig. 5b, c). The subsequent decreases in light penetration in mid-May coincided with increases in Chl and certain measures of tripton (PAV_i, PAV_{Cl}, and Tr). The progressive decrease in SD (Fig. 5f) and increase in K_s (Fig. 5g) over the September-November interval tracked the increases in measures of tripton (Fig. 5b, c, except Tr), that coincided with the progression of fall mixing to the onset of complete turnover (November) and the drawdown of the reservoir (Fig. 5e). The progressive increases in Chl in early fall contributed in part to the patterns for SD and K_s for that interval. However, the major decrease in Chl in November (Fig. 5a), in the absence of a increase in SD (Fig. 5f) and a decrease in K_s (Fig. 5g), indicates ChI was not the primary regulator of light attenuation during this interval. Apparently the impact of this decrease in Chl was compensated by a concurrent increase in tripton.

Concentrations of Chl were somewhat lower, but tripton levels were much greater, and the transparency and extent of light penetration much lower, in Schoharie Reservoir compared to Neversink Reservoir (Figs 3, 5 and 6). Concentrations of Chl exceeded 5 μg l^{-1} in Schoharie Reservoir on only a single occasion, and levels remained below 3 μg l^{-1} over the July–November interval (Fig. 6a). Similar runoff patterns occurred for the primary tributaries of Neversink Reservoir (Fig. 5d) and Schoharie Reservoir (Fig. 6d) over the study interval of 1998, reflecting regional (Fig. 1) precipitation for that period. The patterns of drawdown were also similar (Figs 5e and 6e). Unlike observations for Neversink Reservoir, conspicuous peaks in all the measures of tripton were observed in Schoharie Reservoir following the runoff events (Schoharie Creek, 68% of total inflow) of both May and June (Fig. 6b, c). The greater impact of regional rainfall events on Schoharie tripton levels (Figs 5 and 6) is consistent with its higher TSS loads (Figs 6 and 7) and higher flushing rate (Table 1). Further, unlike the observations for the more dilute Neversink Reservoir, the temporal patterns of all the various measures of tripton remained highly correlated in Schoharie Reservoir (Fig. 6b, c). The levels of tripton decreased abruptly (Fig. 6b, c) following the June runoff event (Fig. 6c) associated with deposition (Effler et al., 2001b). As observed for Neversink Reservoir (Fig. 5), tripton levels increased in Schoharie Reservoir over the fall mixing interval (Fig. 6b, c), in the absence of runoff events (Fig. 6d), indicating this material was supplied by resuspension processes. As in the case of Neversink Reservoir, this process was promoted by drawdown (Fig. 6e) and increased watercolumn turbulence. The temporal patterns of SD (Fig. 6f) and K_s (Fig. 6g) tracked each other well. These patterns appear to have been linked with those of tripton (Fig. 6b, c), but were largely uncoupled from the dynamics of Chl (Fig. 6a).

Variations in SD (as 1/SD) and K_s were well correlated for most of the basins ($R^2 \geq 0.62$), except in the two downstream reservoirs in the Delaware system, where variability in these measures was limited over the study interval (Table 4). The relationship between these two optical properties has often been quantified by the $K_x \cdot$SD product (e.g. Poole & Atkins, 1929; Beeton, 1957; Effler, 1985). Indeed, a product value of 1.9 (Beeton, 1957) has been invoked widely by the water quality modeling community to estimate K_x where only SD observations are available. Average $K_s \cdot$SD products for the study systems ranged from 1.59 to 2.00 (Table 4). The imperfect correlation of these measures and the variability in the $K_s \cdot$SD product have two primary causes: (1) temporal variations in the relative contributions of absorption and scattering (e.g specific attenuation constituents) to overall attenuation (Effler et al., 1988), and (2) measurement errors (Effler, 1985). The lower average $K_s \cdot$SD product values for Cannonsville, Pepacton, and the two basins of Ashokan Reservoir (Table 4) indicate scattering (associated with particles) made relatively greater contributions to overall light attenuation in these systems compared to the other study basins (Effler, 1985). Clearly, these optical measures are imperfect estimators of each other in these systems; i.e. assuming a single $K_x \cdot$SD product for this system of reservoirs, or temporal uniformity for the product for individual basins, would be accompanied by substantial uncertainty (Table 4).

Regulation of dynamics in K_s *and SD*

Performance features (R^2_{adj} and significance at α = 0.05, 0.001) of linear empirical models (e.g. Equations (1)–(4)) in predicting the observed variations in K_s and SD for the study reservoirs are presented here for dependent variable options of: (1) Chl, (2) Tr, (3) FSS, (4) PAV_i, (5) PAV_{Cl}, and (6) PAV_i and Chl (multiple linear regression; Figs 8 and 9). The presentation reflects west-to-east and upstream-to-downstream configuration within the Delaware and Catskill systems; the north basin of West Branch is considered as a separate system (Figs 8 and 9). The strongest relationships for the study basins are presented in Table 5. Certain systematic short-comings were encountered in the analyses. The relatively small number of PAV_i observations for Cannonsville Reservoir limited the analysis for this system. The relatively low variability in K_s, SD, and the attenuating constituents in the downstream reservoirs of the Delaware system (Rondout and the south basin of West Branch) limited the evaluations for these basins.

These empirical analyses indicated tripton was a more important regulator of the seasonal dynamics of K_s (Fig. 8) and SD (Fig. 9) than Chl in most of the study basins. Significant (α = 0.001) Chl-K_s relation-

Table 5. Selected ($R^2 \geq 0.36$) empirical models for SD (as 1/SD) and K_s for study basins, with Chl and/or PAV_i as the attenuating constituent(s)

Reservoir	Relationship	n	p-value	R^2_{adj}
Cannonsville	$1/SD = 0.0193 \cdot Chl + 0.2963$	26	0.0007	0.36
	$K_s = 0.0728 \cdot PAV_i + 0.4292$	13	0.0045	0.49
Pepacton	$1/SD = 0.0438 \cdot PAV_i + 0.2375$	29	0.0003	0.37
Neversink	$1/SD = 0.0447 \cdot PAV_i + 0.1965$	18	0.0030	0.40
	$1/SD = 0.0214 \cdot Chl + 0.1974$	18	0.0004	0.52
	$1/SD = O.O307 \cdot PAV_i + 0.0167 \cdot Chl + 0.1638$	18	0.0069	0.69
	$K_s = 0.0699 \cdot PAV_i + 0.3880$	16	0.0045	0.41
	$K_s = 0.O538 \cdot PAV_i + 0.0134 \cdot Chl + 0.3632$	16	0.0405	0.44
West Branch North	$1/SD = 0.0665 \cdot PAV_i + 0.2185$	17	0.0000	0.72
	$1/SD = 0.0322 \cdot Chl + 0.1817$	17	0.0000	0.69
	$1/SD = 0.0405 \cdot PAV_i + 0.0164 \cdot Chl + 0.1819$	17	0.0137	0.79
	$K_s = 0.0345 \cdot PAV_i + 0.5648$	14	0.0052	0.45
Schoharie	$1/SD = 0.0737 \cdot PAV_i + 0.1190$	16	0.0001	0.64
	$K_s = 0.0841 \cdot PAV_i + 0.4757$	15	0.0007	0.57
Ashokan West	$1/SD = 0.0354 \cdot PAV_i + 0.2809$	28	0.0000	0.76
	$K_s = 0.0423 \cdot PAV_i + 0.4501$	22	0.0000	0.80
Ashokan East	$1/SD = 0.0337 \cdot PAV_i + 0.2365$	29	0.0000	0.52
	$K_s = 0.0677 \cdot PAV_i + 0.3506$	21	0.0000	0.68

ships were not observed for any of the study basins (Fig. 8). Significant ($\alpha = 0.001$) Chl-SD relationships were obtained for three of the basins, Cannonsville (Fig. 9a), Neversink (Fig. 9c), and the north basin of West Branch (Fig. 9f). The better relative performance of Chl for Cannonsville and the north basin of West Branch compared to the other basins is consistent with the higher Chl levels common to these basins (Fig. 3a). Significant ($\alpha = 0.001$) tripton-K_s relationships were observed in all of the Catskill study basins (Fig. 8). Significant ($\alpha = 0.001$) tripton-SD relationships were found for all the basins except Cannonsville (Fig. 9a), Rondout (Fig. 9d), and the south basin of West Branch (Fig. 9e). This result for Cannonsville was influenced greatly by one observation (combination of low SD and PAV_i values); deletion of this value resulted in a significant tripton-SD relationship. Variations in Chl did not explain more than 30% of the variability reported for K_s in any of these basins (Fig. 8). These variations did explain more than 30% of the variability in SD in Cannonsville, Neversink, and the north basin of West Branch, and in the first two cases Chl was the single best predictor of SD (Fig. 9a, c, f). Differences in the performance of these empirical models for K_s and SD should not be considered anomalous, because of the different response of these measures to changes in the relative contributions of the attenuating processes of absorption and scattering (Effler, 1985; Preisendorfer, 1986; Kirk, 1994). Neversink Reservoir was the only basin where inclusion of both PAV and Chl in a multiple linear regression framework substantially improved overall model performance (Fig. 9c). Tripton-based models explained more than 30% of the variability for seven of the nine study basins for both K_s (exceptions of Pepacton (Fig. 8b) and Rondout (Fig. 8d)) and SD (exceptions of Cannonsville (Fig. 9a) and Rondout (Fig. 9d)). The empirical tripton-based models were particularly strong ($R^2_{adj} \geq 0.60$) for the Catskill system basins, where tripton levels are higher (Table 2; Fig. 3b, c). The model for tripton-SD for the north

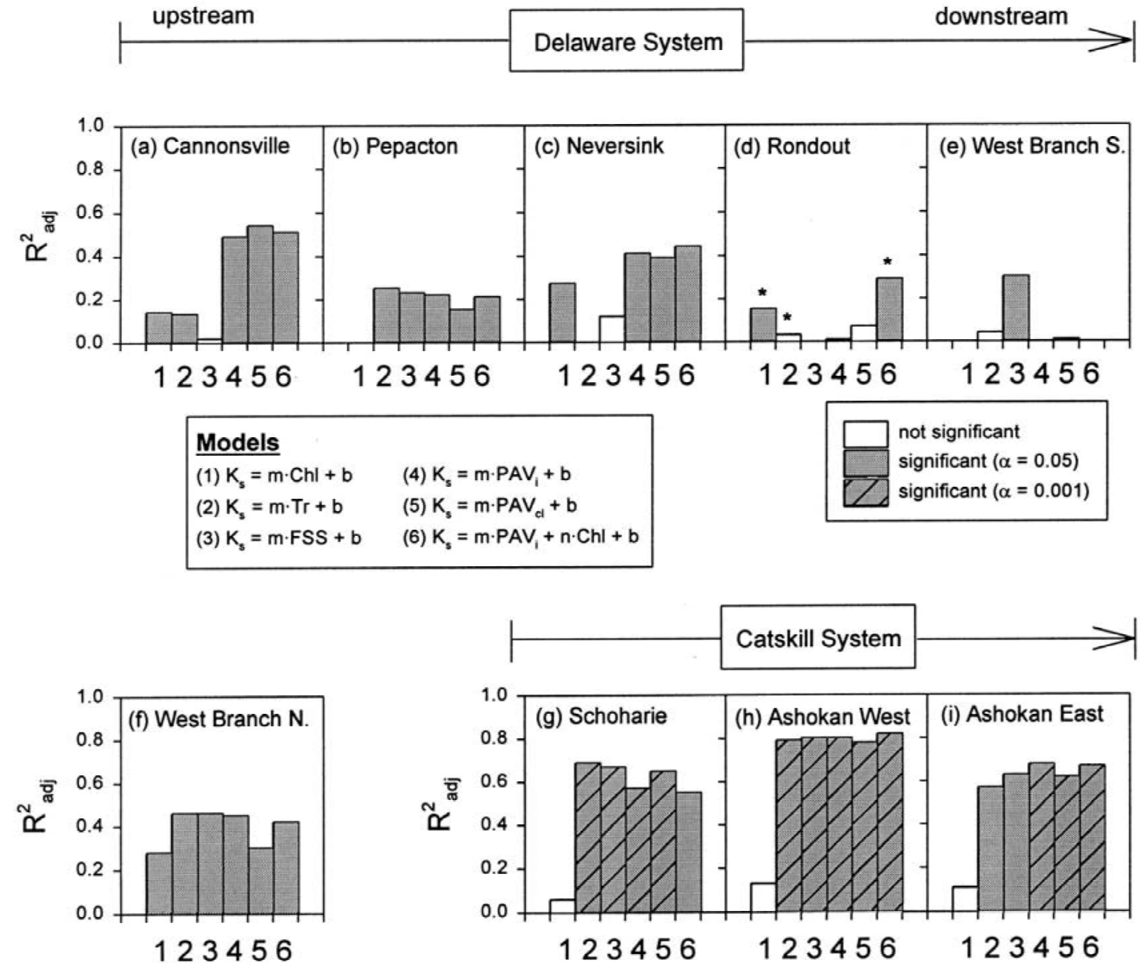

Figure 8. Performance features, R^2_{adj} and significance (α = 0.05, 0.001), of linear empirical models (see key) in predicting observed variations in K_s for five dependent variables (individually, and Chl and PAV$_i$ combined in multiple linear regression): (a) Cannonsville, (b) Pepacton, (c) Neversink, (d) Rondout, (e) south basin of West Branch, (f) north basin of West Branch, (g) Schoharie, (h) west basin of Ashokan, and (i) east basin of Ashokan.

basin of West Branch Reservoir was also quite strong ($R^2_{adj} > 0.70$, Fig. 9f).

A clearly superior measure of the optical effects of tripton for these study basins failed to emerge, though PAV$_i$ from SAX measurements appeared to offer some advantages for the more dilute systems (Figs 8 and 9). The mass concentration measures of tripton (FSS and Tr) generally performed as well as, or even slightly better than, PAV$_i$ for the tripton-enriched Catskill system basins and the north basin of West Branch Reservoir (Figs and 9). The PAV measures of tripton performed better than FSS and Tr in the three upstream basins of the Delaware system in predicting K_s (Fig. 8a–c), and for Pepacton, Neversink, and Rondout Reservoirs in predicting SD (Fig. 9b–d). The gravimetric measures of tripton performed better for the south basin of West Branch Reservoir (Figs 8c and 9c). Performance based on PAV$_{Cl}$, the dominant component (Table 2), was nearly equal to that of PAV$_i$ (Figs 8 and 9).

A number of factors contribute to the imperfect performance of these empirical models for K_s and SD. First, these linear frameworks are compromised by the occurrence of uncoupled variations in more than one attenuating constituent (e.g. Megard et al., 1979), 1980; Oliver & Ganf, 1988), as demonstrated above for Neversink and Schoharie (Figs 5 and 6). Gelbstoff has been omitted from the analyses, however, this constituent only makes a minor contribution to attenuation in these systems (e.g. Effler et al., 1998b).

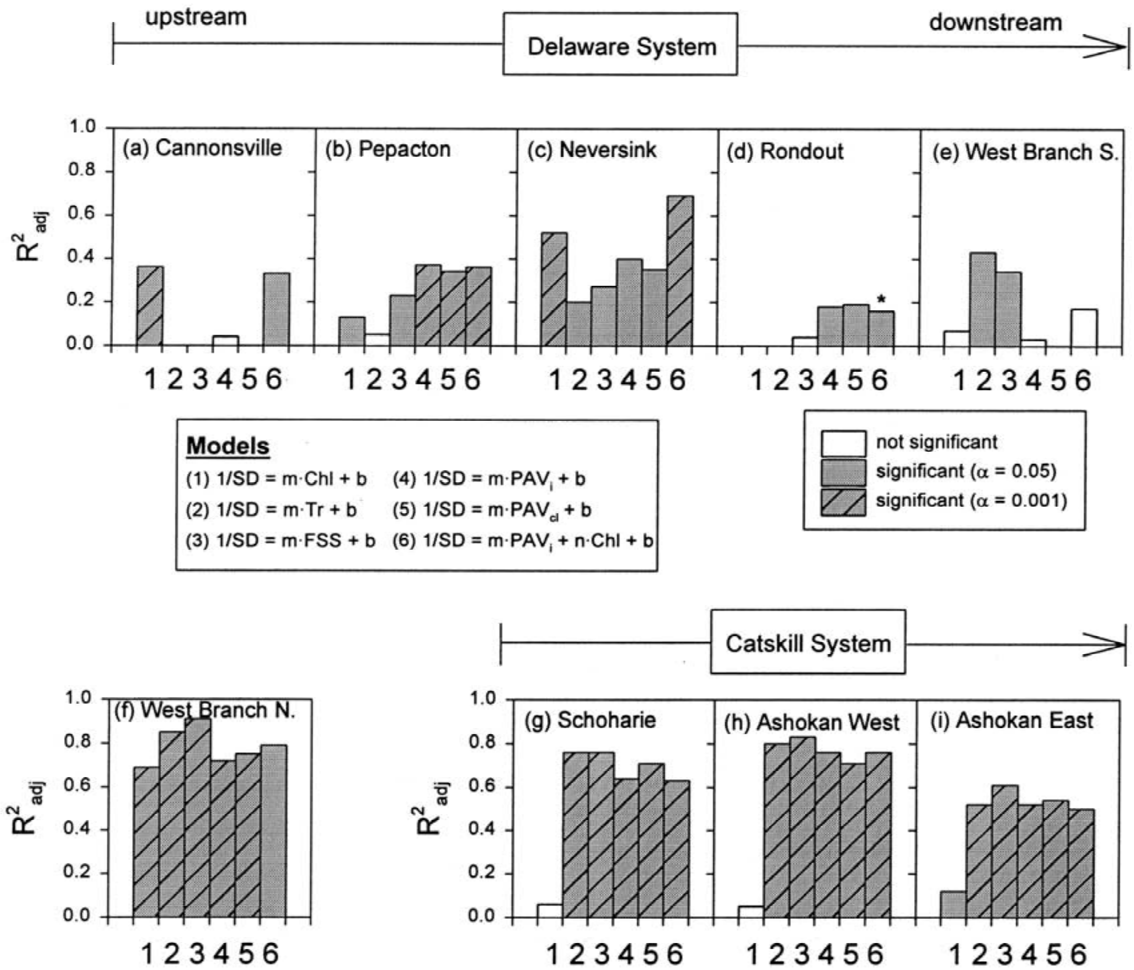

Figure 9. Performance features, R^2_{adj} and significance (α = 0.05, 0.001), of linear empirical models (see key) in predicting observed variations in 1/SD for five dependent variables (individually, and Chl and PAV_I combined in multiple linear regression): (a) Cannonsville, (b) Pepacton, (c) Neversink, (d) Rondout, (e) south basin of West Branch, (f) north basin of West Branch, (g) Schoharie, (h) west basin of Ashokan, and (i) east basin of Ashokan.

Systematic limitations in the measurements also impair model performance. Measurements of K_s and SD are generally considered to be relatively precise (Davies-Colley & Smith, 2001), compared to those for light attenuating constituents, though wind and sky conditions can influence these measurements (particularly SD; Preisendorfer, 1986). The concentration of Chl is an imperfect representation of the light attenuating properties of phytoplankton; e.g. associated with variations in the cellular content of chlorophyll and the differences in attenuating properties of various phytoplankton (Kirk, 1994). Mass concentration metrics of tripton are expected to be imperfect measures of light attenuating properties of this particulate material. The inherent dependence on particle size distribution (Kirk, 1994) may temporally limit empirical relationships, and cause them to differ substantially from system-to-system. The only measure of tripton evaluated here that includes organic detritus was Tr, a variable that did not perform well in the predicting K_s and SD in the more dilute basins of the Delaware system (Figs 8 and 9). Uncertainty in the stoichiometry of phytoplankton (TSS: Chl; Reynolds, 1984) contributes to uncertainty in estimates of Tr. Though the available evidence (Peng et al., 2001; Effler et al., 2001b) indicates organic detritus is not an important contributor to particle populations of the water columns of these systems, this component is doubtless important in some lakes and reservoirs (e.g. Phlips et al., 1995).

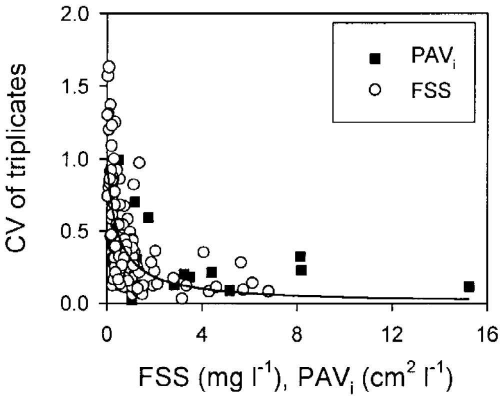

Figure 10. Relationship between coefficient of variability (CV) for analyses of triplicate samples from study reservoirs and the average magnitude for two measures of tripton, FSS and PAV$_i$.

The PAV metric is inherently more closely coupled to optical impacts than mass concentration. Further, such measurements can be adjusted (e.g. Effler et al., 1998b) to accommodate the increased light scattering efficiency of small (e.g. <2.5 μm) particles (Kirk, 1994). Measurements of PAV$_i$ have been reported to be highly correlated to turbidity observations in these basins (Peng et al., 2001) and other systems (e.g. Effler et al., 2000). Turbidity has been found to be a reasonably good surrogate measure of the scattering coefficient in a number of systems (DiToro, 1978; Kirk, 1981; Vant & Davies-Colley, 1984; Weidemann & Bannister, 1986; Effler et al., 1991). However, PAV$_i$ and gravimetric measurements appear to suffer from similar analytical precision short-comings for dilute systems; coefficients of variation from analyses of triplicate samples tended to be substantially higher at the lower levels common to the more dilute basins of this study (Fig. 10). We suspect this is an important factor contributing to the systematically poorer performance of the empirical tripton models for the Delaware system basins.

Deterministic model predictions

The role tripton plays in regulating SD in each of these basins is demonstrated by comparing the distributions of measured values from the long-term monitoring program to those predicted with the model for the case of $b' = 0$ (Fig. 11; paired measurements of Chl and b' as model inputs, see pathway No. 1 of Fig. 2b). The distributions of the observations were in most cases approximately normal, while the predictions generally were more perfectly normal, associated with the very large number of iterations of the Monte Carlo Reservoir calculations (Fig. 11). Tripton is demonstrated to have an important (e.g. Cannonsville Reservoir; Fig. 11a) to dominant (e.g. Schoharie Reservoir; Fig. 2g) effect on prevailing SD observations. One of the smallest effects was predicted for Cannonsville Reservoir, the most eutrophic of the study basins (Fig. 3a); an increase in the mean SD of a factor of ~2.1 was predicted, though substantial overlap of SD values for the $b' = 0$ case with prevailing conditions (Fig. 11a) was projected. The greatest effect was predicted for Schoharie Reservoir, the basin with the highest tripton levels (Fig. 3b, c); an increase in the mean SD of a factor of ~4.8 was predicted, with very little overlap of observations for the $b' = 0$ case with prevailing conditions projected (Fig. 11g). Very limited overlap in the two populations was also predicted for the west basin of Ashokan Reservoir (Fig. 11h), the system with the second highest level of tripton (Fig. 3b, c). The rankings of the mean SD predictions for this scenario generally tracked those of Chl (Fig. 3a), because phytoplankton biomass was the dominant remaining attenuating constituent. The highest values were predicted for Schoharie Reservoir (9.98 m; Fig. 11g), Neversink Reservoir (9.36 m; Fig. 11c), and the south basin of West Branch Reservoir (9.30 m; Fig. 11e): the lowest for Cannonsville Reservoir (4.82 m; Fig. 11a) and the north basin of West Branch Reservoir (7.63 m; Fig. 11f). Using the same model, Effler et al. (2001a) demonstrated tripton's importance in regulating SD in Lake Champlain (U.S.A.) ranged from important to dominant for various portions of this large lake, associated with major spatial differences in the concentrations of these non-phytoplankton particles.

Such simulations are valuable in resolving the relative roles of various attenuating constituents (e.g. Effler et al., 2001a). However, it is important to recognize that these are idealizations. First, although the tripton levels that prevail in these basins can fairly be described as high (e.g. Effler et al. 2001a), some amount of this material is present in even high transparency systems (Davies-Colley & Smith, 2001). Second, it is acknowledged that there is probably some interplay presently between tripton and Chl levels in these basins. Elimination of nearly all tripton from these basins could impact both the availability of light (e.g. Phlips et al., 1995) and nutrients (e.g. James et al., 1997) to support phytoplankton growth, thereby influencing Chl concentrations. The breadths of the distributions predicted for the no tripton ($b' = 0$) case

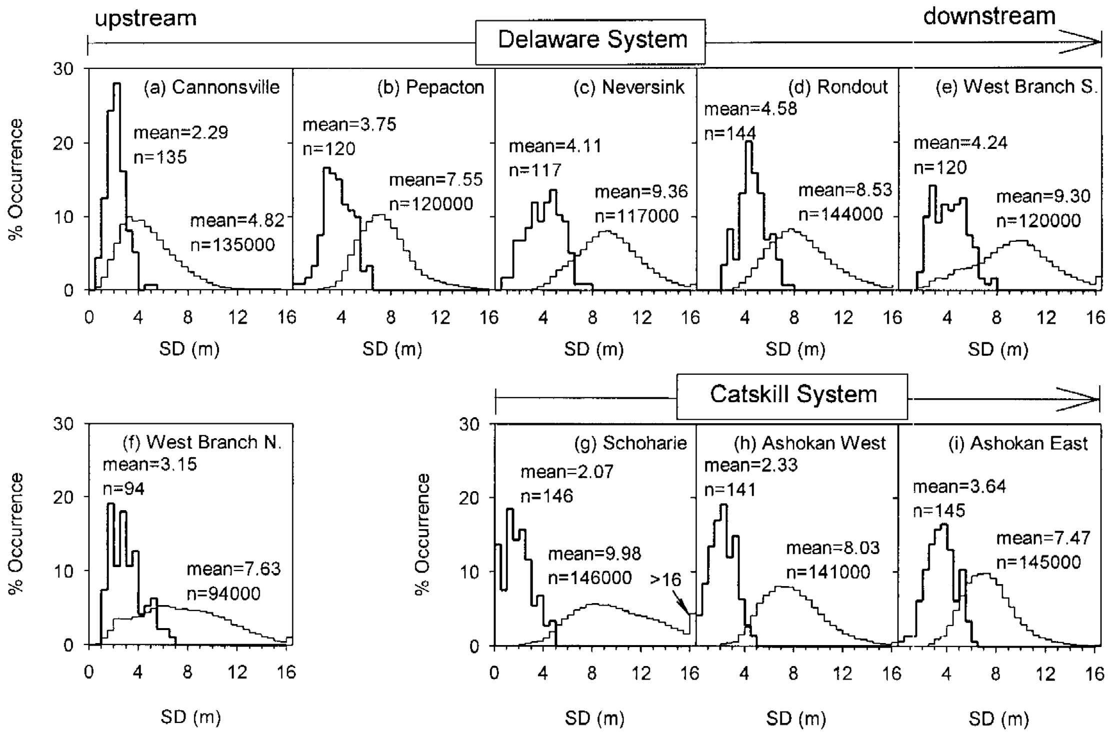

Figure 11. Comparisons of observed distributions of SD for the study reservoirs to predicted distributions for the case of no tripton: (a) Cannonsville, (b) Pepacton, (c) Neversink, (d) Rondout, (e) south basin of West Branch, (f) north basin of West Branch, (g) Schoharie, (h) west basin of Ashokan, and (i) east basin of Ashokan.

reflect the effects of variability/uncertainty in Chl and associated levels of phytoplankton scattering (K_b) and absorption (K_a), other absorption constituents (a_w, and a_y), and ambient conditions during SD measurements (Γ; Fig. 2). The single greatest contributor to this variability is attributable to the variability/uncertainty in K_b (Effler et al., 2001a), associated with the highly disparate magnitudes of scattering by different phytoplankton (e.g. Bricaud et al., 1983). Presentation in this probabilistic format provides a realistic representation of the variability in SD measurements common to systems with these magnitudes and levels of variability of attenuating constituents (Effler et al., 2001a).

Estimates of b' obtained with the deterministic model, based on the paired measurements of Chl and SD (see pathway No. 2 of Fig. 2b) for the comprehensive year of measurements for all the basins, compared favorably with the paired measurements of PAV_i (Fig. 12; R = 0.83). The y-intercept of the best fit linear least squares regression relationship was close to zero, but the very high tripton levels of Schoharie and the west basin of Ashokan had a dis-

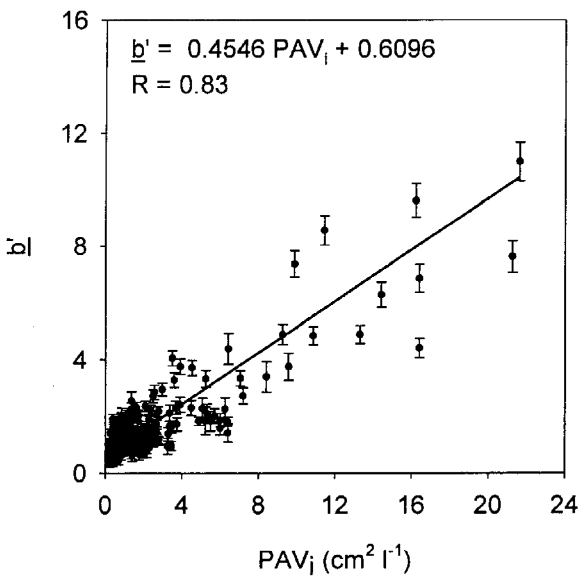

Figure 12. Evaluation of the relationship between paired predictions of tripton scattering (b') measurements of PAV_i for all basins. Dimensions of bars correspond to $\pm$ 1 standard deviation of predictions of b' (n = 1000) with deterministic probabilistic model.

proportionate influence on the apparent strength of the relationship (Fig. 12). Limitations in the PAV_i analysis (e.g. Fig. 10) and the deterministic model framework (Fig. 2; Effler et al., 2001a) doubtless contributed to the observed scatter (Fig. 12). However, we consider this performance encouraging, supporting: (1) the value of PAV_i as a measure of the optical impacts of tripton, (2) the veracity of the deterministic model predictions, and (3) the foregoing findings that depict the importance of tripton in regulating SD and K_s in these basins.

Summary

Differences in SD and K_s amongst the study basins were primarily driven by differences in the level of inorganic tripton of terrigenous origins. The serial configuration of basins within these systems of reservoirs serves to decrease tripton levels (deposition), and thereby increase SD and light penetration in the downstream basins. The strong short-term variations in these optical measures observed in all the study systems, except the downstream basins in the Delaware system (Rondout Reservoir and the south basin of West Branch Reservoir), were driven primarily by the dynamics of this attenuating constituent. Increases in inorganic tripton and decreases in SD and light penetration were documented following runoff events and during drawdown and fall mixing, indicating tributary inflows and sediment resuspension were sources of this material to the water columns of these basins. Tripton-based empirical models explained more than 30% of the observed variability for seven of the nine study basins for both SD and K_s. These models were particularly strong ($R^2 \geq 0.60$) for the three Catskill system basins, where tripton levels were high.

A clearly superior measure of the optical impacts of tripton did not emerge for these study basins from the various analytes included here, however, PAV_i appeared to perform better as a predictor for the more dilute systems. Analytical short-comings (reduced precision) in measures of tripton at low levels of this light attenuating constituent are probably an important factor contributing to the uncertainty concerning the role this material plays in regulating optical properties in dilute systems.

The important, to dominant, role tripton plays in regulating SD in these systems was also demonstrated through application of a probabilistic deterministic optics model. Increases in average SD values by factors of ~ 2 to nearly 5 were predicted for the study basins with this model for the case of no tripton. The veracity of these predictions, and the value of PAV_i as a measure of the optical impacts of tripton, are supported by the strong correlation observed between predictions of tripton scattering, obtained with this model, and PAV_i.

The use of SD as a surrogate measure of trophic state should be considered inappropriate for the reservoirs included in this study. The extent of light penetration would be largely unresponsive to reductions in P loading in most of these basins. Erosion control may be a more appropriate management strategy to achieve increases in clarity in these systems. However, the linkages between external loads of tripton, sediment resuspension, and water column concentrations, as well as the interactions of inorganic tripton and phytoplankton growth (e.g. nutrient and light availability), need to be quantified.

Acknowledgements

Support for this study was provided by the New York City Department of Environmental Protection. The field program was conducted by C. Gandino, B. Wagner, and D. O'Donnell. Y. Bulygina and C.M. Brooks conducted laboratory analyses of chlorophyll *a*.

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