JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
FEBRUARY AMERICAN WATER RESOURCES ASSOCIATION 2004

SEDIMENT RESUSPENSION AND DRAWDOWN IN A WATER SUPPLY RESERVOIR[1]

Steven W. Effler and David A. Matthews[2]

ABSTRACT: The magnitudes and patterns of sediment resuspension are assessed in Cannonsville Reservoir, New York, to quantify and characterize this internal source of sediment. The assessment is based on analyses of sediment trap collections from 10 sites over the spring to fall interval of two years. Temporal and spatial patterns in sediment deposition are demonstrated to be driven by resuspension/redeposition processes. Sediment that had been resuspended and redeposited represented 80 to 96 percent, on average, of the depositing solids collected along the main axis of the lake. About 90 percent of the redeposited sediment was inorganic. Increased resuspension caused by drawdown of the reservoir surface and fall turnover resulted in 10 to 50-fold increases in deposition rates compared to levels observed when the reservoir was full and strongly thermally stratified. Elevated levels of redeposition from resuspension in the reservoir have been driven by both higher water column concentrations of suspended solids and settling velocities. Recurring longitudinal and lateral gradients in resuspension are delineated, establishing that resuspended solids are transported from the riverine to the lacustrine zone and from near-shore to pelagic areas. Resuspension is demonstrated to cause increases in inanimate particle (tripton) concentrations. Higher tripton levels have been observed in years with greater drawdown. Water quality impacts of the resuspension phenomenon are considered.
(KEY TERMS: erosion; sedimentation; sediment resuspension; deposition; sediment traps; benthic nepheloid layers; settling velocity; water quality.)

Effler, Steven W. and David A. Matthews, 2004. Sediment Resuspension and Drawdown in a Water Supply Reservoir. Journal of the American Water Resources Association (JAWRA) 40(1):251-264.

INTRODUCTION

Inanimate particles (tripton) play important ecologic and water quality roles by attenuating light (Kirk, 1985; Weidemann *et al.,* 1985; Effler *et al.,* 2000; 2002a), presenting reactive surfaces (O'Connor, 1988; Simpson *et al.,* 1998), influencing metabolic activity (Hart, 1988; Philips *et al.,* 1995), affecting the concentrations and stoichiometry of particulate constituents (Hecky *et al.,* 1993), and contributing to net sediment deposition (Bloesch, 1995). Sources of tripton to water columns include autochthonous (internal) production by oversaturated mineral phases (e.g., Yin and Johnson, 1984), the watershed (allochthonous, external), and sediment resuspended from bottom deposits (Evans, 1994; Bloesch, 1995). Increasingly, resuspension is being identified as an important, even dominant, source of tripton, and as a driver of related impacts (Dillon *et al.,* 1990; Hellström, 1991; James *et al.,* 1997).

Sediments are resuspended when bottom shear exceeds a critical shear stress for the sediment bed (Evans, 1994; Weyhenmeyer *et al.,* 1997). The critical shear stress is a function of the properties of the sediments. Bottom shear, in the near shore shallow zone, is driven by wind speed and fetch (Bloesch, 1995; Weyhenmeyer *et al.,* 1997). The extent of resuspension is also limited by the pool of resuspendable sediment available. Various approaches have been used to identify and characterize the occurrence of resuspension, including (Bloesch, 1995): (1) transmissiometry to depict the existence of a turbid benthic nepheloid layer, (2) mass balance calculations on total suspended solids (TSS), or other particulate constituents, and (3) analysis of sediment trap collections that include redepositing sediments.

Sediment traps have been employed in a number of studies to assess and quantify features of the resuspension phenomenon (Bloesch, 1982; James and

[1]Paper No. 03087 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2004). **Discussions are open until August 1, 2004.**
[2]Respectively, Director of Research and Research Scientist, Upstate Freshwater Institute, P.O. Box 506, Syracuse, New York 13214 (E-Mail/Effler: sweffler@upstatefreshwater.org).

Barko, 1993; Weyhenmeyer *et al.,* 1995; Weyhenmeyer, 1996). Downward flux (DF), or deposition, as assessed with sediment traps, is regulated by particle concentration and properties, and ambient physical and chemical characteristics (Hutchinson, 1957; Weilenmann *et al.,* 1989). The effects of factors other than concentration are manifested through particle settling velocity (Baines and Pace, 1994; Kozerski, 1994). Higher DFs have been reported in the shallow near shore (e.g., littoral zone) area of lakes, in studies that included multiple horizontal deployments (Bloesch, 1982; Bloesch and Uehlinger, 1986; James and Barko, 1993), reflecting resuspension inputs driven by the effects of wave action. Seasonal increases in resuspension/redeposition have been widely documented in trap studies during intervals of rapid metalimnetic entrainment (Chambers and Eadie, 1981; Weyhenmeyer, 1996; Effler *et al.,* 2001) and turnover (Bloesch, 1982, 1995; Weyhenmeyer, 1996) that are attributable to increased turbulence throughout the water column.

The setting for resuspension in the near shore zone of reservoirs that experience substantial drawdown is more dynamic than for lakes as the sediments exposed to wave action and other forms of turbulence at depth change with the lowering of the water level (Effler *et al.,* 1998a). All other factors being equal, the pool of resuspendable sediment is expected to be greater for these reservoirs, because portions of the reservoir bottom that were previously below the wave base can accumulate particles that are subject to resuspension as the water surface drops. Thus, drawdown is expected to promote resuspension (Effler *et al.,* 1998a, 2001).

In this paper, the magnitude and patterns of sediment resuspension are assessed in a reservoir that experiences drawdown through resolution of downward flux in time and space, based on analysis of sediment trap collections. These patterns and attendant limnological and reservoir operations information are evaluated to identify regions of resuspension, mediating physical processes, and the effect of drawdown. The role the resuspension process plays in influencing tripton levels in the reservoir, and impacts of this material, is considered.

SYSTEM DESCRIPTION

Cannonsville Reservoir (latitude 42°02´46´´, longitude 75°22´24´´, at dam) is located in upstate New York, approximately 190 km from New York City (NYC) (Figure 1). This impoundment is NYC's newest (filling started in 1965) and third largest (of 19) water supply reservoir. The reservoir is used primarily as a drinking water supply and to maintain flows in downstream portions of the Delaware River. The reservoir has a crest capacity of 373×10^6 m^3, a surface area of 19.3×10^6 m^2 (i.e., mean depth, when full of approximately 19 m), and a maximum depth near the dam of approximately 49 m. The reservoir has a maximum length of 27.4 km and a shoreline length of approximately 74 km (L.M. Wood, 1979, unpublished report). The reservoir is a soft water eutrophic system (Effler and Bader, 1998) with a dimictic stratification regime. The soils in the 1,162 km^2 watershed are considered to be highly erodable (A.P. Bader, 1990, unpublished report). The vast majority of the external loading of sediment to the reservoir occurs during runoff events (Longabucco and Rafferty, 1998).

Wide seasonal and interannual differences in runoff occur in the region that cause substantial variability in hydrologic and morphometric features of the reservoir (Owens *et al.,* 1998b). The annual average completely mixed flushing rate of Cannonsville Reservoir over the 1969 to 1995 interval was 2.6/y, with a range of 1.9 to 3.6/y, and a coefficient of variation of 18 percent (Owens *et al.,* 1998b). Drawdown of the reservoir surface (water surface elevation, WSE) has occurred in almost every year of operation of this impoundment, a feature observed for many reservoirs. Maximum drawdown usually occurs in the August to October interval (Effler and Bader, 1998). The extent of drawdown is substantial; the average annual maximum is 15.9 m (Effler *et al.,* 2001), corresponding to 33 percent of full capacity. Wide interannual variations in this hydrologic feature have also occurred in response to natural variations in runoff (Owens *et al.,* 1998b). Features of the stratification/vertical mixing regime of the reservoir depend on the extent of drawdown (e.g., the duration of stratification decreases as the extent of drawdown increases) (Effler and Bader 1998; Owens *et al.,* 1998a).

Mass balance analyses support the position that allochthonous inputs do not make substantial direct (i.e., before initial deposition) contributions to DF assessed by sediment trap collections in this system (Effler *et al.,* 2001), though these external inputs may become noteworthy over brief intervals following particularly severe runoff events. Effler *et al.* (2001) reported a ratio of deposition of TSS from the epilimnion of the reservoir to the external load for the spring to fall interval of 1995 to be 7.3. Further, there are no known autochthonous inputs of tripton for the system (e.g., this dilute system is not oversaturated with respect to common mineral phases). Thus, tripton deposition and levels in the reservoir's water column are regulated by resuspension inputs.

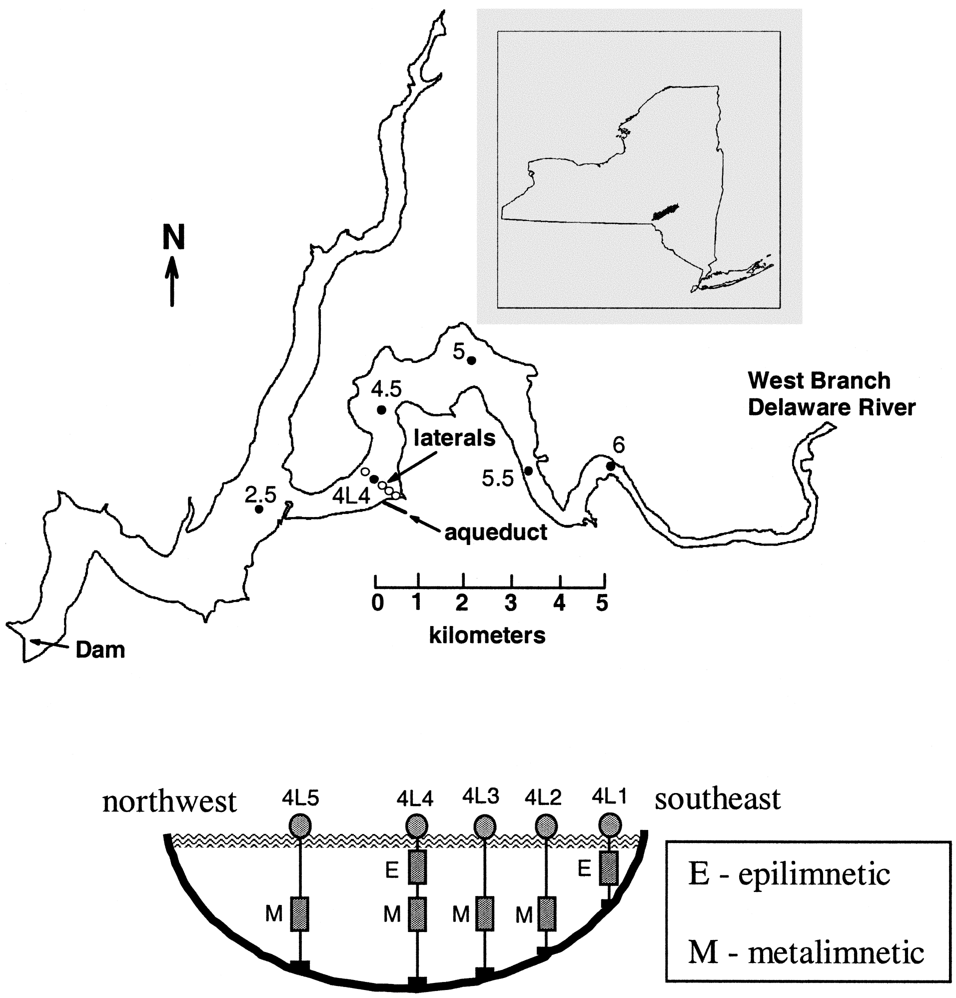

Figure 1. Cannonsville Reservoir, Sediment Trap Deployment Sites, With Position in New York (inset). Cross Section at Site 4 With Schematic of Sediment Trap Positions.

METHODS

Trap design followed the unifying recommendations of a number of investigators, as recently reviewed by Bloesch (1996). The traps were cylindrical PVC tubes with an aspect ratio (height/diameter) of six. The diameter of the trap opening was 7.6 cm. Traps were deployed vertically in groups of three, and the openings were maintained close to horizontal by subsurface air filled polyethylene containers (Effler and Brooks, 1998). Traps were deployed continuously over the May to October interval of 2001 and mid-April through October interval of 2002. No preservatives were used in traps to prevent decomposition for reasons discussed by Rosa *et al.* (1991). Trap samples were collected weekly, well within the recommended range of deployment intervals (Rosa *et al.,* 1991).

Traps were deployed at 10 sites, six along the longitudinal axis, and four additional locations along a lateral transect (one shared site, 4L4; Figure 1), to resolve spatial patterns. The longitudinal transect extends from the upstream riverine section [Site 6; zonation scheme of Kimmel and Groeger (1984), applied by Effler and Bader (1998)] to a downstream lacustrine location (Site 2.5). The water supply intake adjoins Site 4, which is also within the lacustrine zone (Effler and Bader, 1998). The primary/prefix numbers of the monitoring sites correspond to those established for long-term monitoring and specialty studies (Effler and Bader, 1998). Metalimnetic deployments were made at all but the shallowest near shore site (4L1). This vertical position delineates the net deposition out of the epilimnion into the hypolimnion. This flux is a gross deposition within the context of the hypolimnion that is subject to further modification (e.g., resuspension inputs, degradation losses) within this layer. Epilimnetic deployments have been avoided in a number of trap studies because of concerns for potential overtrapping promoted by Langmuir circulation (Bloesch and Burns, 1980). However, epilimnetic deployments have been used by several investigators (Dillon *et al.,* 1990; James and Barko, 1993; Weyhenmeyer *et al.,* 1995). An epilimnetic deployment (opening at depth of 2 m) was adopted at Site 4L1 in an effort to resolve resuspension in the near shore zone. An epilimnetic (2 m) deployment was added at Site 4L4 for the study interval of 2002 to evaluate the extent to which these fluxes match metalimnetic observations. Deployments were readjusted (vertically) as drawdown proceeded in an effort to maintain metalimnetic positions. However, conversion to epilimnetic deployment was unavoidable at shallower upstream sites as drawdown proceeded. Collection had to be terminated at these locations when depth limited access.

There was no visual evidence of loss of collected particulate material during retrieval of trap samples, as the traps always contained relatively low turbidity water overlying the deposited material. Resuspension and loss of collected particles during handling of traps was unlikely, as a horizontal velocity of approximately 24 cm/s would be necessary (Bloesch and Burns, 1980). Depth averaged (equal portions from 0, 2, and 4 m) water column samples were collected at Sites 4L4, 5, and 6 at the time of trap collection. Sediment trap and water column samples were analyzed for suspended solids (APHA, 1992), including TSS and fixed (inorganic) suspended solids (FSS). All three metalimnetic trap collections at 4L4 were analyzed for TSS in both years to assess the precision of the combined effects of collection of depositing sediments, and sample handling and analysis.

Vertical profiles of temperature (T) and beam attenuation coefficient (transmissometry) at 660 nm ($\mathbf{c}_{660}$; WetLabs C Star) were made with a Seabird Sealogger Profiler (Model SDE25) at Sites 2.5, 4L4, 5, and 6 in 2001 and at all six sites along the longitudinal axis in 2002. Readings were recorded at a rate of 8/s with an instrument descent rate of approximately 1.2 m/s. Values of $\mathbf{c}_{660}$ (m^{-1}) are proportional to the scattering coefficient.

Downward fluxes are represented as areal rates (units of g/m^2/day). Fluxes were determined for TSS (DF_{TSS}) and FSS (DF_{FSS}) for each deployment interval and site from the mass of the constituent collected in the trap (W; g), the duration of trap deployment (t; d), and the area of the trap opening (A; m^2) according to the relationship

$$DF = W/(A \times t) \tag{1}$$

Settling velocity (SV; m/d) was estimated for the metalimnetic trap deployments for TSS and FSS for each deployment interval at Site 4L4, 5, and 6 according to

$$SV = DF/PC \tag{2}$$

where PC is the particulate concentration in the epilimnion (g/m^3). The value of PC was determined as the average concentration of the depth integrated water column samples collected on the days of deployment and collection (e.g., Effler and Brooks, 1998). Some uncertainty in SV is unavoidable associated with the disparity in the temporal scales of the measurements of W (an integrated value) and PC (based on instantaneous values). Further, the value of SV calculated in this manner represents a "mean" for a range of settling velocities that produce the observed deposition. This range may be quite wide for certain constituent-ecosystem combinations and thereby limit the utility of SV as a descriptor of the settling characteristics of a heterogeneous particle population that has a spectrum of settling velocities (Kozerski, 1994). However, it has been included here to depict spatial patterns of the deposition process.

The method of Weyhenmeyer *et al.* (1995) was used to estimate: (1) the contribution of resuspended sediment versus autochthonous organic particles to DF_{TSS}, (2) the contribution of inorganic particles (FSS) to DF_{TSS}, and (3) the contribution of resuspended organic particles to overall organic particle deposition. The calculations are based on linear least squares regressions of DF_{TSS} versus DF_{FSS} (Weyhenmeyer *et al.,* 1995). Assumptions of this approach include (Weyhenmeyer *et al.,* 1995): (1) direct inputs of allochthonous particles do not significantly contribute to DF, (2) the contribution of plankton to deposition can be represented by the y-intercept of the regression expression, (3) the impact of diatom (a mix of organic and inorganic components) deposition on the regression expression, and related calculations, is unimportant, and (4) resuspended sediment contains the same organic fraction as bottom sediments. These calculations were made on a site specific basis for both years, for deployments along the reservoir's longitudinal axis.

RESULTS AND DISCUSSION

Data Quality and Representativeness

The average coefficients of variation (CV) for DF_{TSS} for Site 4L4 in 2001 and 2002 were 9 and 10 percent, respectively. These generally match levels reported previously for these protocols, applied to different systems (Womble *et al.,* 1996; Effler and Brooks, 1998; Effler *et al.,* 2001), and those presented in the review of Rosa *et al.* (1991) for multiple trap deployments at a single site.

The DFs observed for the epilimnetic and metalimnetic deployments at 4L4 in 2002 for TSS were highly correlated (r = 0.97) for the total population of paired measurements (Figure 2). The relationship was substantially less strong (r = 0.76) for the 22 observations for which DFs were less than 5 g/m^2/d. The mean DF for the epilimnetic deployment (3.05 g/m^2/d) was 10 percent lower (contrary to concerns for overtrapping) than the metalimnetic value (3.39 g/m^2/d). However, for populations of DFs less than 5 g/m^2/d, the epilimnetic mean DF was 21 percent lower. Since epilimnetic values of DF for upstream sites late in the study intervals (necessitated by drawdown) and at the near shore Site 4L1 were generally greater than 5 g/m^2/d (subsequently), their comparability is supported for the following analyses.

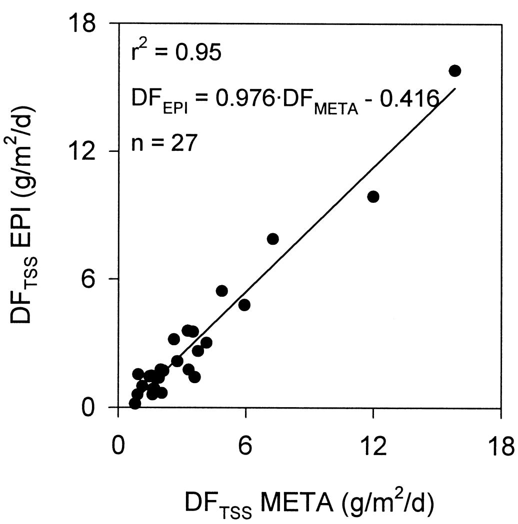

Figure 2. Evaluation of the Relationship Between DF_{TSS} Values From Paired Epilimnetic and Metalimnetic Deployments at Site 4L4 in 2002, With Summary of Results of Linear Least Squares Regression.

Drawdown and DF Dynamics

The extent and dynamics of drawdown were substantially different for the study intervals of 2001 (Figure 3a) and 2002 (Figure 3h). The reservoir was full at the start of trap deployments in May 2001 and remained nearly full until mid-July. Subsequently, the WSE dropped progressively and rapidly through the remainder of the 2001 study interval. By late October, the WSE had been drawn down approximately 23 m (Figure 3a), substantially more than the long term average maximum drawdown. The reservoir remained drawn down by approximately 11 m at the start of trap deployments in early April 2002 (Figure 3h). WSE increased progressively until late June, when the reservoir approached full capacity. This was followed by progressive drawdown until late September. A reincrease in WSE occurred starting in mid-October (Figure 3h). The extent of drawdown in October was much greater in 2001 than 2002.

Strong temporal variations in DF_{TSS} and DF_{FSS} occurred at all deployment sites in both years (Figure 3b to 3g, and 3i to 3n). The dynamics in overall suspended solids deposition were driven by those of the inorganic fraction, as variations in DF_{FSS} explained equal to or greater than 99 percent of the variations in DF_{TSS} at each site in both years, according to linear least squares regression. Since DF_{FSS} is associated primarily with resuspension in this system (Effler *et al.,* 1998a; cf. Weyhenmeyer *et al.,* 1995), the dynamics of deposition in the reservoir were driven by those of redeposition of resuspended sediment. The lowest DFs occurred during intervals of strong thermal stratification (represented by the top-to-bottom T difference, ΔT) (Figure 3) when the reservoir was relatively full. Decreases in DFs from upstream (e.g., riverine zone) to downstream (e.g., lacustrine zone) positions were apparent during the summer interval, a gradient that was generally maintained during other portions of the study period. The highest DFs and resuspension were observed in late summer and fall, with the approach to fall turnover (decreasing ΔT) and the progression of drawdown (Figure 3). The exception, Site 6 in 2002 (Figure 3i), was due to the timing of the discontinuation of trap deployment dictated by lack of adequate water depth. Further, there was temporal and spatial structure in the onset of the higher DFs of late summer/fall, with delays moving from the riverine to lacustrine zones [e.g., early August at Site 6 (Figure 3b) and mid-September at Site 4 in 2001 (Figure 3f)]. These differences generally track the timing of loss of T stratification at these locations, indicating an important interplay with this seasonal phenomenon. DF values were 10- to 50-fold higher in fall compared to levels observed when the reservoir was full and strongly stratified.

The interplay between the dynamics of T stratification and patterns of particle levels, and thus potential for deposition, are described for the late August to mid-October interval of 2001 at Site 4 through paired T and $\mathbf{c}_{660}$ profiles for four dates (Figures 4a through 4d). The imperfect relationship between optical and gravimetric measures of suspended solids is acknowledged (Davies-Colley and Smith, 2001), but the vertical detail of $\mathbf{c}_{660}$ profiles is invaluable in depicting the distribution of particles. The increase in $\mathbf{c}_{660}$ in the lower waters with the approach to the sediments, evident in late August (Figure 4a), depicts the presence of a benthic nepheloid layer (BNL). This is widely

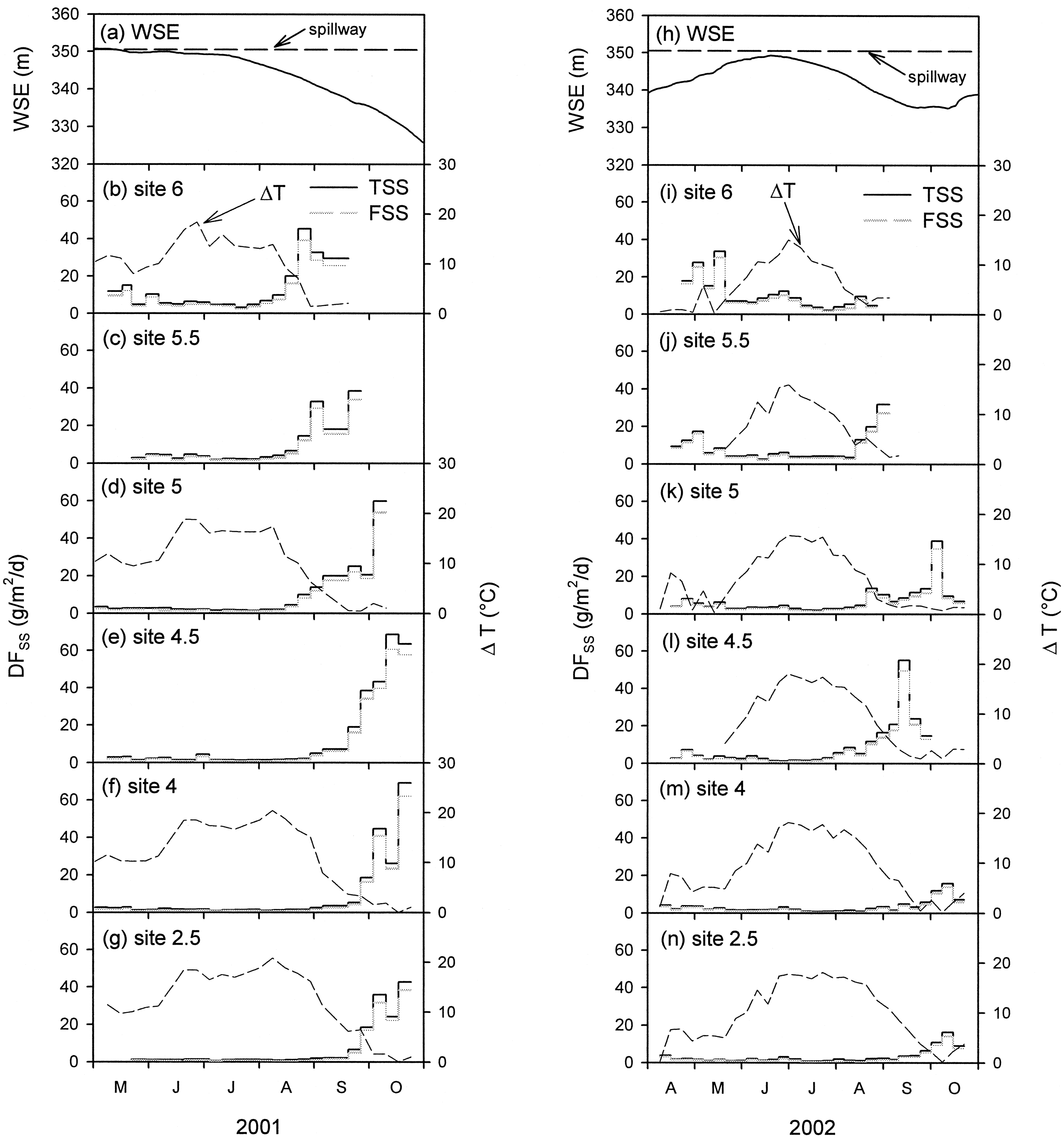

Figure 3. Time Series of WSE, DF_{TSS} , DF_{FSS} , and ΔT for Metalimnetic Deployments Along the Reservoir's Primary Axis in 2001 and 2002: (a) WSE, 2001, (b) Site 6 DFs and ΔT, 2001, (c) Site 5.5 DFs, 2001, (d) Site 5 DFs and ΔT, 2001, (e) Site 4.5 DFs, 2001, (f) Site 4 DFs and ΔT , 2001, (g) Site 2.5 DFs and ΔT, 2001, (h) WSE, 2002, (i) Site 6 DFs and ΔT, 2002, (j) Site 5.5 DFs and ΔT, 2002, (k) Site 5 DFs and ΔT, 2002, (l) Site 4.5 and ΔT, 2002, (m) Site 4 DFs and ΔT, 2002, and (n) Site 2.5 DFs and ΔT, 2002.

accepted as a manifestation of the operation of resuspension processes (e.g., Halfman and Johnson, 1989; Pierson and Weyhenmeyer, 1994; Bloesch, 1995; Effler *et al.,* 1998a). By mid September the BNL had expanded vertically, as the epilimnion deepened and drawdown continued (Figure 4b). By early October, epilimnetic $\mathbf{c}_{660}$ levels had increased (Figure 4c), at least in part from entrainment of the enriched stratified layers. Over the early to mid-October interval, T stratification was eliminated and $\mathbf{c}_{660}$ increased in the well mixed water column by more than a factor of two. Entrainment of the BNL contributes at least in part to the transport of resuspended sediment into upper layers. Using available hypsographic data for

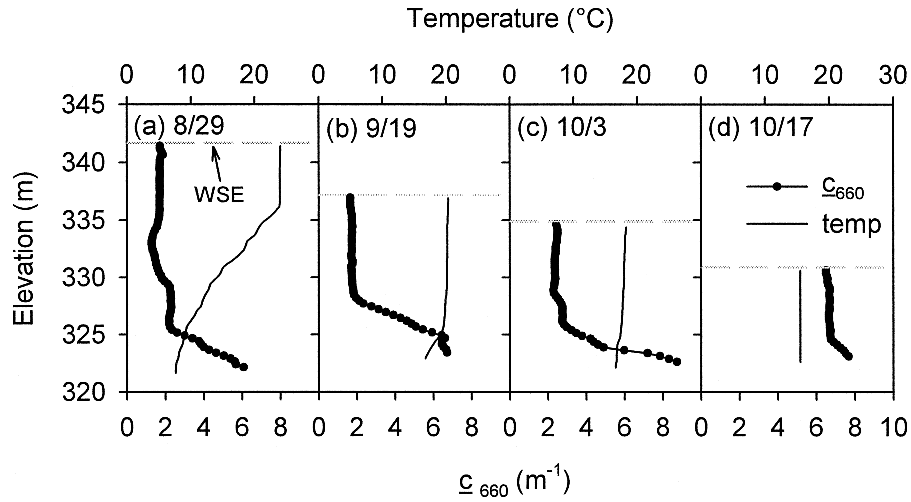

Figure 4. Vertical Profiles of T and $\mathbf{c}_{660}$ at Site 4L4 in 2001: (a) August 29, (b) September19, (c) October 3, and (d) October 17.

that portion of the reservoir (Gelda *et al.,* 1998), a net increase was estimated in the water column content of $\mathbf{c}_{660}$ (treating it in a manner akin to concentration) from October 3 to October 17 of more than 20 percent. This suggests the increased $\mathbf{c}_{660}$ levels in the upper waters were more than could be explained solely by entrainment of the BNL. Apparently, additional resuspension of bottom sediments occurred under these isothermal (i.e., turbulent) conditions.

Analysis of paired measurements of water column concentrations of TSS and FSS, and estimates of SV_{TSS} and SV_{FSS}, are valuable in evaluating the relative roles of particle concentrations versus settling characteristics in driving the dynamics of DF. Paired time series presented for Site 4 in 2001 (Figure 5) are generally representative of patterns observed at the other deployment sites. The patterns for WSE (Figure 5a) and DF (Figure 5b) are included again for reference. Water column concentrations of FSS were approximately 2 mg/l for the first couple of weeks of May, but were closer to 1 mg/l, subsequently, through much of September (Figure 5c). The organic component of TSS [volatile SS (VSS) = TSS - FSS] was approximately 2 mg/l from May through early July (Figure 5c). A conspicuous increase in TSS (approximately 8 mg/l), driven by a peak in VSS, occurred over the mid-July to late August interval, associated with a phytoplankton bloom (mostly cyanobacteria; Upstate Freshwater Institute, unpublished data). The SV_{FSS} was approximately 1 m/d through mid-August. Values of SV_{FSS} and SV_{TSS} were nearly equal over portions of May and June, indicating inorganic and organic particles were settling at similar rates. Given the greater density of inorganic particles, this condition necessarily reflected a compensating effect of larger particle sizes for the organic particles. Values of SV_{FSS} exceeded SV_{TSS} by a wide margin during the July/August phytoplankton bloom, reflecting a well known feature of many cyanobacteria of slow settling rates (Reynolds, 1984). These patterns in TSS, FSS, SV_{TSS}, and SV_{FSS} resulted in only modest variations in DFs, relative to those imparted by the strong increases observed in September and October from increased resuspension (Figures 5b through 5d). Resuspension drove increases in (re-)deposition in September and October through a combination of increases in the concentration of FSS (maximum of approximately 7 mg/l; Figure 5c) and SV_{FSS} (Figure 5d). Both features are reasonable expectations for intervals of elevated resuspension. Increased shear stress delivered to sediments is expected to increase both the mass of sediment mobilized and inclusion of larger particles that will settle more rapidly (Bloesch, 1982; Weyhenmeyer, 1996). The absence of strong thermal stratification over this interval doubtless also contributed to the higher SV_{FSS}, though this effect on the reported increase is small.

Estimates of Contributions of Resuspension to DF

Strong relationships (r^2 greater than 0.99) between DF_{TSS} and DF_{FSS} were observed for all deployment sites in both years, as illustrated here for Site 4 in 2001 (Figure 6). Deletion of the four highest pairs of DFs, measured in September and October (Figure 3e), resulted in a significantly (p less than 0.05) higher slope (1.255). This reflects the greater relative contribution of resuspended inorganic particulate matter to total deposition during this period of extreme drawdown.

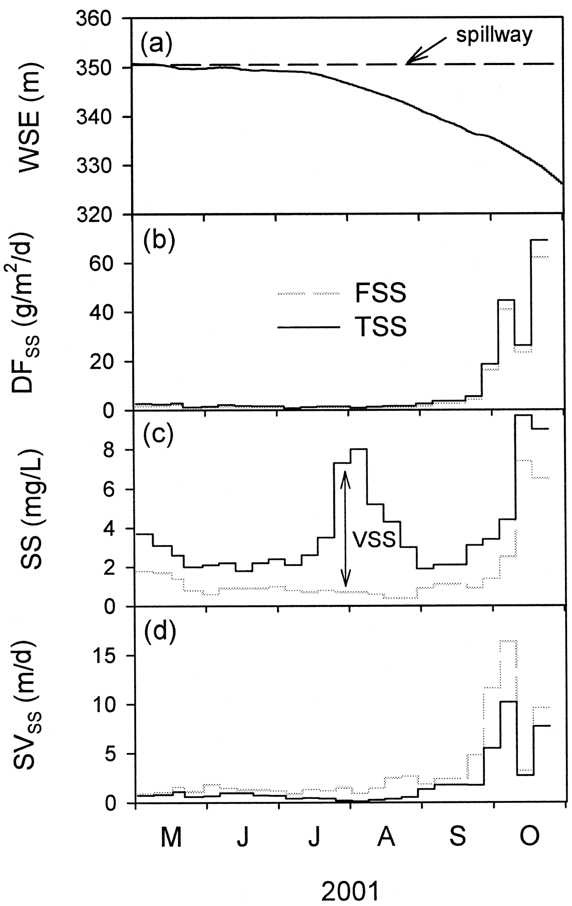

Figure 5. Time Series for Site 4 in 2001: (a) WSE, (b) DF_{TSS} and DF_{FSS}, (c) TSS and FSS, and (d) SV_{TSS} and SV_{FSS}.

The character of these relationships (e.g., Figure 6) is consistent with arguments presented by Weyhenmeyer *et al.* (1995), suggesting that the diatom component of the phytoplankton does not interfere with the application of their approach to estimate resuspension for this system. The estimated DF of autochthonous organic particles for this case, corresponding to the y-intercept (Weyhenmeyer *et al.*, 1995), was 0.43 g/m^2/d. The highest y-intercept values were observed for Site 6 (0.63 and 0.84 g/m^2/d, in 2001 and 2002, respectively). Values for all other sites were in a rather narrow range (0.28 to 0.47 g/m^2/d), except Site 5.5 in 2002 (0.15 g/m^2/d). This single value for autochthonous deposition for the late spring/fall interval can be viewed as a weighted central value, based on the mode of determination. Thus, it is an oversimplification of the dynamics of DF for autochthonous organic particles, as pronounced variations in phytoplankton biomass occur in the water column of the reservoir (Effler and Bader, 1998). The slopes of the 12 (six sites, two years) relationships were within a narrow range of 1.074 to 1.142.

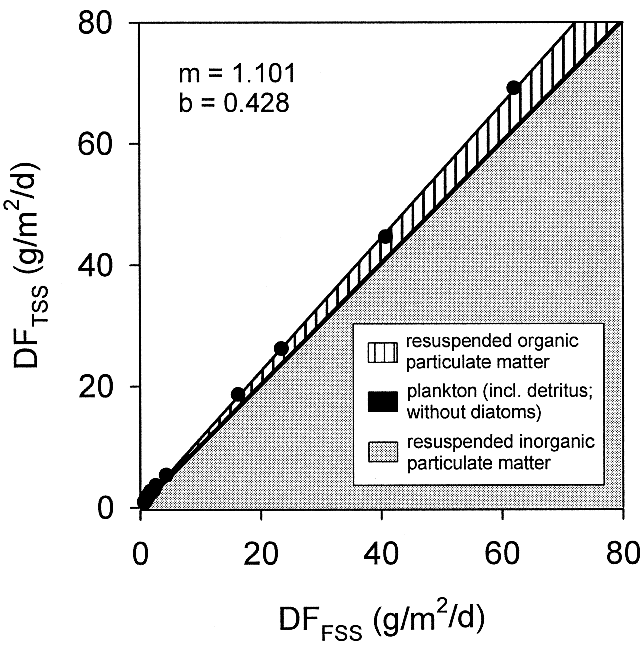

Figure 6. Relationship Between DF_{TSS} and DF_{FSS} at Site 4 in 2001, With Identification of Components Contributing to DF_{TSS}, According to the Method of Weyhenmeyer *et al.* (1995).

Statistics for estimates of contributions of resuspension to deposition, calculated according to the protocol of Weyhenmeyer *et al.* (1995) (e.g., Figure 6), are presented for each site for both years (Table 1). Mean and median values for the contributions of resuspension to DF_{TSS} were generally quite similar. The calculated contribution of resuspension to deposition differed according to site and study year (Table 1). However, on average, resuspension dominated at all sites in both years, ranging from 80 (Site 2.5, 2001) to 96 percent (Site 5.5, 2002). These values are similar to estimates reported by Weyhenmeyer *et al.* (1995) for Lake Erken and Lake Limmaren (83 to 94 percent). Further, Evans (1994) speculated that 80 to 90 percent of DF_{TSS} in most lakes was attributable to resuspension. A distinct gradient in the mean value was obtained in 2001, with progressive decreasing contributions from the riverine zone (92 percent) through the lacustrine zone (80 percent; Table 1). The gradient appears to be recurring, as it was also observed in 2002, starting at Site 5.5 rather than Site 6. This deviation probably was a manifestation of the

TABLE 1. Estimates of Contributions of Resuspension to Deposition, According to Site and Study Year, by the Methodology of Weyhenmeyer *et al.* (1995).

		Total Resuspension (percent)			Inorganic Resuspension (percent)			Organic Resuspension (percent)		
Site	Year	Range	Median	Mean	Range	Median	Mean	Range	Median	Mean
6	2001	83 to 100	83	92	72 to 87	81	81	35 to 90	54	61
	2002	62 to 98	89	88	58 to 91	82	82	13 to 73	37	38
5.5	2001	78 to 100	89	90	70 to 90	80	80	30 to 90	45	51
	2002	87 to 100	97	96	77 to 92	86	85	65 to 96	79	81
5	2001	76 to 100	89	88	69 to 90	80	80	24 to 94	35	47
	2002	83 to 100	94	94	74 to 94	84	83	35 to 93	59	61
4.5	2001	69 to 100	85	86	63 to 92	76	78	18 to 94	35	46
	2002	71 to 100	90	89	63 to 92	81	80	18 to 92	39	48
4L4	2001	67 to 100	79	81	61 to 91	72	74	13 to 94	22	34
	2002	62 to 100	90	87	56 to 91	81	77	17 to 86	44	46
2.5	2001	54 to 100	80	80	49 to 92	73	72	11 to 92	21	36
	2002	43 to 100	91	85	38 to 95	80	75	18 to 88	41	44

Note: Total Resuspension is the percentage of DF_{TSS} attributed to resuspended sediment. Inorganic Resuspension is the percentage of DF_{TSS} attributed to resuspended inorganic sediment. Organic Resuspension is the percentage of DF_{VSS} attributed to resuspended organic sediment.

lack of collections at Site 6 in September of 2002 when resuspension levels almost certainly would have been elevated (Figure 3b and 3i). The lower boundary of the ranges occurred in intervals of strong T stratification and low DF, and generally decreased from the riverine to lacustrine zone. The lower bound (seasonal minima) contributions of resuspension over the study intervals of 2001 and 2002, at Site 2.5, were 54 and 43 percent, respectively. Thus, resuspension was an important contributor to DF_{TSS} at all sites throughout the study.

Resuspended inorganic particulate material was the dominant component of deposition at all sites, representing from 72 to 85 percent of DF_{TSS}, on average (Table 1). The corresponding average contribution of organic particulates in the resuspended sediment was 7 to 12 percent (the average was 10 percent). These values are in reasonably good agreement with the composition of surficial sediments reported for six sites in the reservoir; the average composition was 7.5 percent VSS (Erickson and Auer, 1998). Though the organic fraction of resuspended sediment is estimated to be minor relative to overall resuspension in this system, it is an important component of overall organic deposition (resuspension + phytoplankton production), representing approximately 40 percent on average at the lacustrine sites (Table 1). The contribution was somewhat higher at the upstream sites. The particularly high estimate at Site 5.5 in 2002 (81 percent corresponds to the case of the lowest y-intercept, and is considered an outlier. The value at Site 6 in 2002 may have been influenced by the lack of September observations.

Spatial Gradients

The observations have been time segmented to assess the effect of drawdown on longitudinal patterns of resuspension and redeposition of FSS (the dominant component, Table 1) in the reservoir. Time segments of May to July, August to September, and October have been specified. The different extents of drawdown embedded in these three seasonal time segments for the two years (Table 2) offer the opportunity to investigate the impacts of this forcing condition on resuspension.

TABLE 2. Average Values of Water Surface Elevation (WSE) for Three Seasonal Time Segments and Two Years.

	WSE (m)	
Time Segment	2001	2002
May to July	349.4	347.2
August to September	341.1	339.2
October	330.9	336.9

Decreasing gradients in DF_{FSS} extending from the riverine zone into the lacustrine zone (Figures 7a and 7b) depict transport of resuspended sediment from upstream to downstream portions of the reservoir. Multiple comparisons of means for the May to July interval of 2001 and 2002 indicate a particularly strong gradient in upstream portions of the reservoir (Table 3). Sites 6, 5.5, and 5 were significantly different from each other in both study years (Table 3). More extreme drawdown during May to July of 2002 apparently caused stronger gradients in resuspension to prevail in upstream portions of the reservoir (Figure 7a) (e.g., mean DF_{FSS} values at Sites 6, 5.5, and 5 were significantly higher in 2002 than 2001 (Table 3). The increase in resuspension from drawdown in the May to July interval of 2002 (Table 2) was attenuated over the riverine and transition (e.g., Site 5) (Effler and Bader, 1998) zones, as the populations of DF_{FSS} for Sites 4.5, 4, and 2.5 were not significantly different for the two years (Table 3).

A clear gradient in DF_{FSS} continued to be manifested in 2001 over the drawdown interval of August to September (Figure 7b). The average values at all six sites were higher compared to the May to July interval (Figures 7a and 7b). This indicates increased transport of resuspended sediment from upstream portions of the reservoir to its lacustrine zone, under these conditions of extensive drawdown. Conditions were less clear cut for this interval in 2002. Values were not available for the entire interval for Sites 6 and 5.5 (Figures 3i and 3j), and deposition was greater at Site 4.5 than at Site 5 (Figure 7b). However, the higher DFs during the August to September interval of 2002 (Figure 7b) compared to observations for the May to July interval (Figure 7a) are indicative of increased sediment resuspension from drawdown. Observations to support the evaluation of the impact of the additional drawdown of October 2001 are limited to deployments at Sites 4 (Figures 3f and 3m) and 2.5 (Figures 3g and 3n). The average of the 2001 observations was four-fold greater than those of 2002 in October, providing further support for the position that drawdown increases sediment resuspension.

The documented longitudinal gradients in DF_{FSS} were driven by gradients in both water column concentrations of FSS (Figures 7c and 7d) and settling properties of depositing inorganic particles, as reflected in the calculated values of SV_{FSS} (Figures 7e and 7f). Of these two factors, SV_{FSS} was by far the primary driver for the May to July interval in both years (compare Figures 7c and 7e). The gradient(s) in SV_{FSS} indicates a mobilization of larger particles in upstream regions that settle more rapidly. The SV_{FSS} estimates for Sites 6 and 5 were significantly (p less than 0.004; t-test on log-transformed variables) higher for this interval in 2002 (Figure 7c), indicating that the increased resuspension in this year was associated with mobilization of more sediment and of sediment that contained relatively more large particles. Increases in FSS concentrations and SV_{FSS}

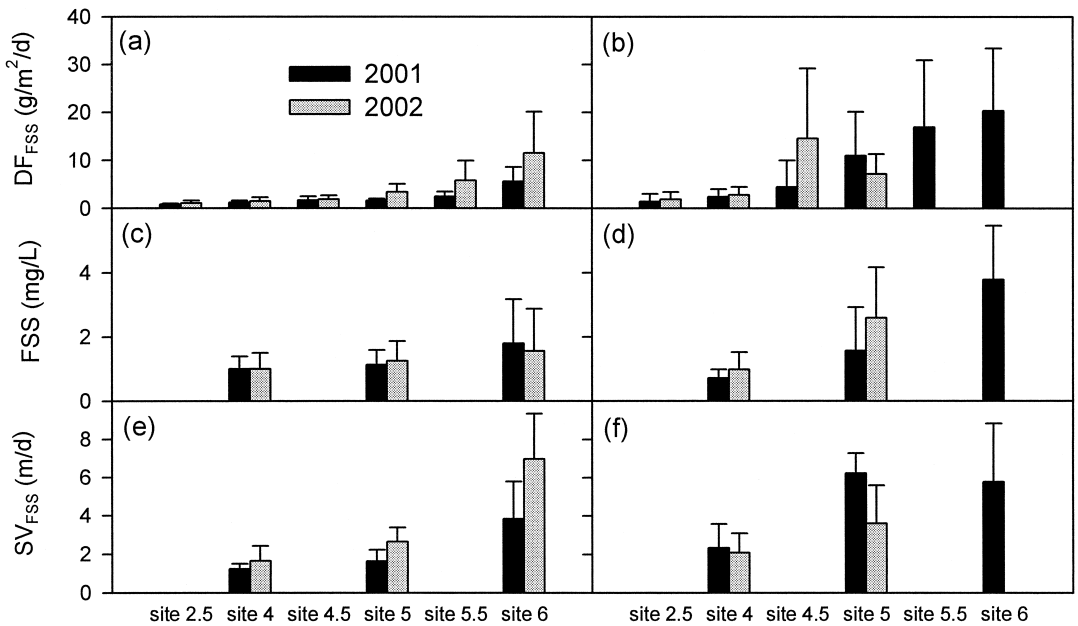

Figure 7. Comparison of Longitudinal Patterns of Features of FSS Deposition for 2001 and 2002: (a) DF_{FSS}, May to July, (b) DF_{FSS}, August to September, (c) Water Column FSS, May to July, (d) Water Column FSS, August to September, (e) SV_{FSS}, May to July, and (f) SV_{FSS}, August to September. Bars represent averages for the interval; dimension of vertical line is + 1 standard deviation.

contributed more equally to upstream deposition of resuspended sediments during the greater drawdown interval of August to September (Figures 7a and 7e). Particularly high concentrations of FSS prevailed at Site 6 (average of approximately 4 mg/l) during this interval in 2001 (Figure 7d). The similarity of SV_{FSS} values at Sites 6 and 5 (Figure 7f) suggest there may be an upper bound to particle sizes mobilized in upstream portions of the reservoir during drawdown.

TABLE 3. Statistical Evaluation of Interannual and Longitudinal Differences Among Deployment Sites for the May to July Interval.

Site	DF_{FSS} ($g/m^2/d$) 2001	DF_{FSS} ($g/m^2/d$) 2002	p-Value	Longitudinal Groupings 2001	Longitudinal Groupings 2002
6	5.6	11.5	0.02	A	A
5.5	2.5	5.8	0.003	B	B
5	1.6	3.4	0.0003	C	C
4.5	1.7	1.9	0.38	C	D
4	1.2	1.5	0.52	C	DE
2.5	0.8	1.1	0.12	D	E

Note:P-values are from t-tests performed on log-transformed measurements of DF_{TSS} for the May to July interval of 2001 and 2002. Sites that share the same letter are not significantly (α = 0.05) different according to the Duncan test for *post-hoc* multiple comparisons.

Deposition rates of FSS were higher along the lateral transect moving away from the centerline Site 4L4 toward the shore, as represented here by the ratios of DF_{FSS} at transect sites to observations at 4L4. Time series of the ratios are presented for the site adjacent (within approximately 10 m) to shore (4L1) and the next site along the transect (4L2; Figure 1) for 2001 (Figures 8a and 8b). Localized nearshore resuspension is clearly depicted by the much higher DFs observed at Site 4L1 during stratification; the ratio exceeded five for a number of paired deployments (Figure 8a). The ratio approached unity in late September and October (Figure 8a) during fall turnover, when the highest levels of resuspension of the study interval were observed at Site 4L4 (Figure 3f). This closure among the lateral sites during turnover indicates the magnitude of resuspension at the near shore site prevailed across the lateral axis in that interval. Features of the temporal structure in near shore resuspension (Figure 8a) may reflect influences of variations in bottom shear (i.e., wind), changes in the character of near shore sediments as the reservoir was drawn down, and perhaps modest variations in the position of this deployment relative to the shoreline. Given the major reductions in the ratio for the deployment located less than 100 m away (4L2; Figure 8b), the distance of the 4L1 deployment from shore (redeployed weekly as part of sample collection) is expected to have an important effect on the measured magnitude of resuspension. Despite the much lower ratio values at 4L2, it is important to note that DF_{FSS} was systematically higher at this site than at the center of this transect (4L4). The ratio was greater than 1.00 for 80 percent of the paired deployments (inset of Figure 8b).

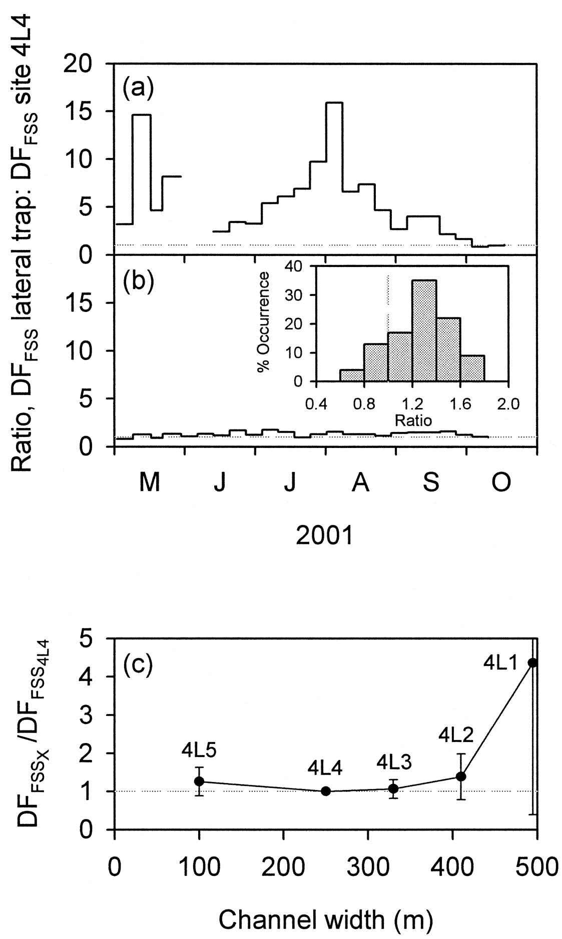

Figure 8. Lateral Patterns in DF at Site 4 in 2001: (a) Time Series of Ratio of DF_{TSS} at Site 4L1 to DF_{TSS} at Site 4L4, (b) Time Series of Ratio of DF_{TSS} at Site 4L2 to DF_{TSS} at Site 4L4, and (c) Lateral Transect of Average Ratios of DF_{TSS}, With Centerline Deployment (4L4) Values as Denominator. Bars are ± 1 standard deviation.

The lateral transect of average ratio values for the 2001 study interval (Figure 8c) shows gradients in resuspension/redeposition extending from the shoreline(s) toward the center of the basin. This lateral structure depicts the movement of sediment resuspended in the near shore zone toward pelagic portions of the water column. The gradient was particularly steep adjoining the shore, where resuspension as a result of wave action is expected (Evans, 1994; Bloesch, 1995). The much higher DF_{FSS} in the near-shore zone also reflects the redeposition of the larger, more rapidly settling, particles (e.g., Bloesch, 1982), leaving the smaller, more slowly settling particles to be transported to the pelagic zone.

Impacts of Resuspension

Resuspension causes increased concentrations of inorganic tripton in the water column of the reservoir, both within the upper waters (Figure 5c) and as a BNL above the bottom sediments (Figure 4). Effler *et al.* (1998a) reported increases in inorganic tripton in the upper waters of Cannonsville Reservoir during an interval of extensive drawdown in 1995, composed primarily of clay minerals and secondarily quartz. Interannual differences in resuspension, as mediated by the extent of reservoir drawdown, cause year-to-year differences in tripton levels. This is illustrated here through a linear least squares regression analysis of the dependence of average concentration of FSS over September and October at Site 4 (Upstate Freshwater Institute, 1995, unpublished data; New York City Department of Environmental Protection, 1996 to 2000, unpublished data) on the average WSE for the same interval (Figure 9). Higher levels of inorganic tripton were generally observed in the years of greater drawdown; variations in WSE explained 62 percent of the variations in FSS (Figure 9).

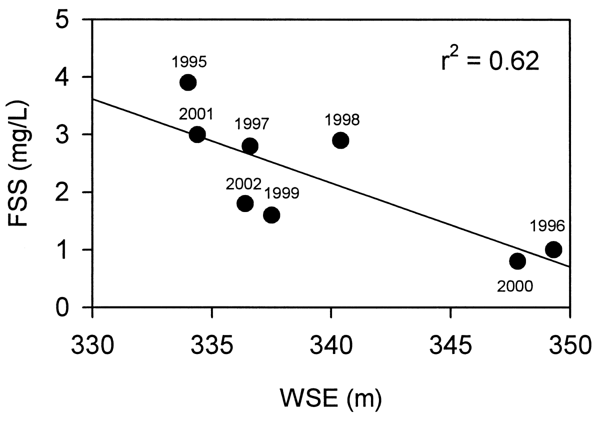

Figure 9. Evaluation of the Relationship Between the Average Water Column FSS and WSE, for September and October, at Site 4, for the Period 1995 to 2002.

Tripton is of concern because of impacts on optical properties, particularly as a contributor of turbidity, a regulated parameter for water supplies (Davies-Colley and Smith, 2001). Effler *et al.* (1998b) reported that inorganic tripton was the dominant component of turbidity in the upper waters of Cannonsville Reservoir in 1995, a major drawdown year (Figure 9). This component represented 68 percent of the turbidity on average, and changes in inorganic tripton turbidity explained 85 percent of the variations in overall turbidity over the 1995 study interval. Inorganic tripton particles attenuate light primarily through the process of light scattering (Effler *et al.,* 2002b). Effler *et al.* (2002b) reported tripton was an important regulator of both light attenuation and water clarity (Secchi disc) in Cannonsville Reservoir. Increases in attenuation from tripton decreases the light available to support phytoplankton growth. This effect was represented in a phytoplankton model for the reservoir (Doerr *et al.,* 1998) by an empirical expression that increased the nonphytoplankton (e.g., tripton) component of light attenuation as WSE decreased. Other trophic levels can also be affected. For example, high inorganic tripton levels have been reported to interfere with filter feeding by daphnids (Vanderploeg *et al.,* 1987; Hart, 1988).

The reactive surfaces of inorganic tripton are also of interest in Cannonsville Reservoir within the context of their effects on phosphorus (P) cycling and primary production. Clay minerals are well known to have a high affinity for P (Kuo and Lotse, 1972; Edzwald *et al.,* 1976; Mayer and Gloss, 1980). Progressive increases in particulate P (PP) in the epilimnion of the reservoir from mid-summer through fall in 1995, in the absence of systematic changes in phytoplankton biomass, were attributed to increases in resuspended tripton based PP (Effler and Bader, 1998). Much of the PP deposition over the same interval was attributed to tripton (Effler and Brooks, 1998). Sediment resuspension can support phytoplankton growth through desorption of P from resuspended particles (Sondergaard *et al.,* 1992; James *et al.,* 1997). These particles become enriched through exposure to elevated dissolved P concentrations in the pore waters of sediment deposits. Pore water concentrations can become quite high relative to overlying waters, associated with the decomposition of deposited organic (e.g., phytoplankton) material (Wetzel, 2001), promoting sorption of P to exposed particles. Upon resuspension, particles enter a much more dilute environment that promotes desorption of P from the particles. Thus, the resuspension process acts as a conduit for the recycle of P from deposited phytoplankton back into the water column. Research is presently underway to incorporate this internal source of P in the mechanistic phytoplankton model for the reservoir, which will guide management efforts to limit eutrophication in this system.

CONCLUSIONS

Resuspended sediment is the dominant component of depositing solids in Cannonsville Reservoir. This component represented 80 to 96 percent, on average, of the solids collected with sediment traps at sites along the main axis of the reservoir. Minimum contributions (approximately 50 percent) occurred seasonally in lacustrine areas when the reservoir was full and thermal stratification was strong. About 90 percent of the redeposition/resuspended sediment was inorganic, generally consistent with the composition of the surface sediments of the reservoir. About 50 percent of the depositing organic solids in the lacustrine zone was resuspended organic material (e.g., the other 50 percent was attributable to planktonic production). Temporal and spatial patterns of deposition in the reservoir were driven by resuspension.

Drawdown of the reservoir surface and fall turnover caused dramatic increases in resuspension. Downward fluxes were 10- to 50-fold greater in these periods compared to levels observed during intervals of strong thermal stratification when the reservoir was nearly full. Entrainment of benthic nepheloid layers (BNLs), another manifestation of resuspension, is in part responsible for increases in water column tripton levels and redeposition observed during the fall mixing interval. Occurrences of elevated levels of redeposition in time and space were driven by higher water column solids concentrations and higher settling velocities, manifestations of increased turbulence. Clear longitudinal and lateral gradients in resuspension were delineated, establishing the transport of resuspended sediment from the riverine to the lacustrine zone and from near-shore to pelagic areas.

Sediment resuspension causes increases in inanimate particles (tripton) in the water column of the reservoir, both in the upper and lower (BNL) layers. This causes increased turbidity, a particular concern for water supply reservoirs, and increased light attenuation and decreased water clarity. Further, sediment resuspension almost certainly augments phytoplankton growth by recycling (sorption/desorption processes) phosphorus from deposited/decayed plankton into the productive layers of the reservoir. Analysis of historical data established that higher levels of inorganic tripton have generally been observed in the years of greater drawdown. Thus there are water quality impacts, mediated by sediment resuspension processes, for operating the reservoir according to its intended uses. Sediment resuspension is probably an important component of deposition and source of tripton in many surface water systems, but particularly reservoirs that experience substantial drawdown.

ACKNOWLEDGMENTS

This research was funded by the New York City Department of Environmental Protection. The field program was conducted by B.A. Wagner, M. Spada, and A.P. Prestigiacomo. Laboratory analyses were performed by C.M. Matthews and J. Kaser. This is Contribution No. 220 of the Upstate Freshwater Institute.

LITERATURE CITED

APHA (American Public Health Association), 1992. Standard Methods for the Examination of Water and Wastewater (18th Edition). American Public Health Association, Washington, D.C.

Baines, S.B. and M.L. Pace, 1994. Relationships Between Suspended Particulate Matter and Sinking Flux Along a Trophic Gradient and Implications for the Fate of Planktonic Production. Canadian Journal of Fisheries and Aquatic Sciences 51:25-36.

Bloesch, J., 1982. Inshore-Offshore Sedimentation Differences Resulting From Resuspension in the Eastern Basin of Lake Erie. Canadian Journal of Fisheries and Aquatic Sciences 39:748.

Bloesch, J., 1995. Mechanisms, Measurement and Importance of Sediment Resuspension in Lakes. Marine and Freshwater Research 46:295-304.

Bloesch, J., 1996. Towards a New Generation of Sediment Traps and a Better Measurement/Understanding of Settling Particulate Flux in Lakes and Oceans: A Hydrodynamic Protocol. Aquatic Science 58:283-296.

Bloesch, J. and N. M. Burns, 1980. A Critical Review of Sediment Trap Technique. Schweizerische Zeitschrift für Hydrologie 42:15-55.

Bloesch, J. and U. Uehlinger, 1986. Horizontal Sedimentation Differences in a Eutrophic Swiss Lake. Limnology and Oceanography 31:1094-1109.

Chambers, R.L. and B.J. Eadie, 1981. Nepheloid and Suspended Particulate Matter in South-Eastern Lake Michigan. Sedimentology 28:439-497.

Davies-Colley, R.J. and D.G. Smith, 2001. Turbidity, Suspended Sediment, and Water Clarity: A Review. Journal of American Water Resources Association (JAWRA) 37:1085-1101.

Dillon, P.J., R.D. Evans, and L.A. Molot, 1990. Retention and Resuspension of Phosphorus, Nitrogen, and Iron in a Central Ontario Lake. Canadian Journal of Fisheries and Aquatic Sciences 47:1269-1274.

Doerr, S.M., E.M. Owens, R.K. Gelda, M.T. Auer, and S.W. Effler, 1998. Development and Testing of a Nutrient-Phytoplankton Model for Cannonsville Reservoir. Lake and Reservoir Management 14:301-321.

Edzwald, J.K., D.C. Toensing, and M.C. Leung, 1976. Phosphate Adsorption Reactions With Clay Minerals. Environmental Science and Technology 10:485-490.

Effler, S.W. and A.P. Bader, 1998. A Limnological Analysis of Cannonsville Reservoir, NY. Lake and Reservoir Management 14:125-139.

Effler, S.W. and C.M. Brooks, 1998. Dry Weight Deposition in Polluted Onondaga Lake, New York, U.S.A. Water, Air and Soil Pollution 103:389-404.

Effler, S.W., C.M. Brooks, M.G. Perkins, N. Ohrazda, D.A. Matthews, D.L. Johnson, M.T. Auer, J.A. Bloomfield, and S. Quinn, 2000. The Effects of Terrigenous Inputs on Spatial

Patterns of Water Quality Indicators in South Lake, Lake Champlain. Journal of Great Lakes Research 26:366-383.
Effler, S.W., R K. Gelda, D.L. Johnson, and E.M. Owens, 1998a. Sediment Resuspension in Cannonsville Reservoir. Lake and Reservoir Management 14:225-237.
Effler, S.W., C.M. Matthews (Brooks), and D.A. Matthews, 2001. Patterns of Gross Deposition in Reservoirs Enriched in Inorganic Tripton. Canadian Journal of Fisheries and Aquatic Sciences 58:2177-2188.
Effler, S. ., D.A. Matthews, M.G. Perkins, D.L. Johnson, F. Peng, M.R. Penn, and M.T. Auer, 2002a. Patterns and Impacts of Inorganic Tripton in Cayuga Lake. Hydrobiologia 482:137-150.
Effler, S. W., M. G. Perkins, and D. L. Johnson, 1998b. The Optical Water Quality of Cannonsville Reservoir: Spatial and Temporal Patterns, and the Relative Roles of Phytoplankton and Inorganic Tripton. Lake and Reservoir Management 14:238-253.
Effler, S.W., M.G. Perkins, N.Ohrazda, D.A. Matthews, R.K. Gelda, F. Peng, D.L. Johnson, and C.L. Stepczuk, 2002b. Tripton, Transparency and Light Penetration in Seven New York Reservoirs. Hydrobiologia 468:213-232.
Erickson, M.J. and M.T. Auer, 1998. Chemical Exchange at the Sediment Water Interface of Cannonsville Reservoir. Lake and Reservoir Management 14:266-277.
Evans, R.D., 1994. Empirical Evidence of the Importance of Sediment Resuspension in Lakes. Hydrobiologia 284:5-12.
Gelda, R.K., E.M. Owens, and S.W. Effler, 1998. Calibration, Verification, and an Application of a Two-Dimensional Hydrothermal Model [CE-QUAL-W2(t)] for Cannonsville Reservoir. Lake and Reservoir Management 14:186-196.
Halfman, B.M. and T.C. Johnson, 1989. Surface and Benthic Nepheloid Layers on the Western Arm of Lake Superior, 1983. Journal of Great Lakes Research 15:15-25.
Hart, R.C., 1988. Zooplankton Feeding Rates in Relation to Suspended Sediment Content: Potential Influences on Community Structure in a Turbid Reservoir. Freshwater Biology 19:123-139.
Hecky, R.E., P. Campbell, and L.L. Hendzel, 1993. The Stoichiometry of Carbon, Nitrogen, and Phosphorus in Particulate Matter of Lakes and Oceans. Limnology and Oceanography 38:709-724.
Hellström, T., 1991. The Effect of Resuspension on Algal Production in a Shallow Lake. Hydrobiologia 213:183-190.
Hutchinson, G.E., 1957. A Treatise of Limnology. I. Geography, Physics and Chemistry. John Wiley and Sons, New York, New York.
James, R.T., J. Martin, T. Wool, and P.F. Wang, 1997. A Sediment Resuspension and Water Quality Model of Lake Okeechobee. Journal of the American Water Resources Association (JAWRA) 33:661-680.
James, W.F. and J.W. Barko, 1993. Sediment Resuspension, Redeposition, and Focusing in a Small Dimictic Reservoir. Canadian Journal of Fisheries and Aquatic Sciences 50:1023-1028.
Kimmel, B.C. and A.W. Groeger, 1984. Factors Controlling Primary Production in Lakes and Reservoirs: a Perspective. Lake and Reservoir Management, EPA 4405-84-001, pp. 277-281.
Kirk, J.T.O., 1985. Effects of Suspensoids (Turbidity) on Penetration of Solar Radiation in Aquatic Ecosystems. Hydrobiologia 125:195-209.
Kozerski, H.P., 1994. Possibilities and Limitations of Sediment Traps to Measure Sedimentation and Resuspension. Hydrobiologia 284:93-100.
Kuo, S. and E.G. Lotse, 1972. Kinetics of Phosphate Adsorption by Calcium Carbonate and Ca-Kaolinite. Soil Science Society of America Journal 36:725-729.
Longabucco, P. and M.R. Rafferty, 1998. Analysis of Material Loading to Cannonsville Reservoir: Advantages of Event-Based Sampling. Lake and Reservoir Management 14:197-212.
Mayer, L.M. and S.P. Gloss, 1980. Buffering of Silica and Phosphate in a Turbid River. Limnology and Oceanography 25:12-22.
O'Connor, D.J., 1988. Models of Sorptive Toxic Substances in Freshwater Systems. II. Lakes and Reservoirs. Journal of Environmental Engineering Division ASCE 114:533-551.
Owens, E.M., S.W. Effler, S.M. Doerr, R.K. Gelda, E.M. Schneiderman, D.G. Lounsbury, and C.L. Stepczuk, 1998a. A Strategy for Reservoir Model Forecasting Based on Historic Meteorological Conditions. Lake and Reservoir Management 14:322-331.
Owens, E.M., R.K. Gelda, S.W. Effler, and J.M. Hassett, 1998b. Hydrologic Analysis and Model Development for Cannonsville Reservoir. Lake and Reservoir Management 14:140-151.
Philips, E.J., F.J. Aldridge, C.L. Schelske, and T.L. Crisman, 1995. Relationships Between Light Availability, Chlorophyll *a*, and Tripton in a Large Shallow Subtropical Lake. Limnology and Oceanography 40:416-421.
Pierson, D.C. and G.A. Weyhenmeyer, 1994. High Resolution Measurements of Sediment Resuspension Above an Accumulation Bottom in a Stratified Lake. Hydrobiologia 284:43-57.
Reynolds, C.S., 1984. Ecology of Freshwater Phytoplankton, Cambridge Studies in Ecology. Cambridge University Press, England.
Rosa, F., J. Bloesch, and D.E. Rathke, 1991. Sampling the Settling and Suspended Particulate Matter (SPM). *In:* Handbook of Techniques of Aquatic Sediment Sampling, A. Mudroch and S. C. Macknight (Editors). CRC Press, Ann Arbor, Michigan, pp. 97-130.
Simpson, S.L., S.C. Apte, and G.E. Batley, 1998. Effect of Short-Term Resuspension Events on Trace Metal Speciation in Polluted Anoxic Sediments. Environmental Science and Technology 32:620-625.
Sondergaard, M., P. Kristensen, and E. Jeppesen, 1992. Phosphorus Release From Resuspended Sediment in the Shallow and Wind-Exposed Lake Arreso, Denmark. Hydrobiologia 228:91-99.
Vanderploeg, H.A., B.J. Eadie, J.R. Liebig, S.J. Tarapchak, and R.M. Gloger, 1987. Contribution of Calcite to the Particle-Size Spectrum of Lake Michigan Seston and Its Interactions With the Plankton. Canadian Journal of Fisheries and Aquatic Sciences 44:1898-1914.
Weidemann, A.D., T.P. Bannister, S.W. Effler, and D.L. Johnson, 1985. Particulate and Optical Properties During $CaCO_3$ Precipitation in Otisco Lake. Limnology and Oceanography 30:1078-1083.
Weilenmann, U., C.R. O'Melia, and W. Stumm, 1989. Particle Transport in Lakes: Models and Measurements. Limnology and Oceanography 34:1-18.
Wetzel, R.G., 2001. Limnology: Lake and Reservoir Ecosystems. Academic Press, New York, New York.
Weyhenmeyer, G.A., 1996. The Influence of Stratification on the Amount and Distribution of Different Settling Particles in Lake Erken. Canadian Journal of Fisheries and Aquatic Sciences 53:1254-1262.
Weyhenmeyer, G.A., L. Håkanson, and M. Meili, 1997. A Validated Model for Daily Variations in the Flux, Origin, and Distribution of Settling Particles Within Lakes. Limnology and Oceanography 42:1517-1529.
Weyhenmeyer, G.A., M. Meili, and D.C. Pierson, 1995. A Simple Method to Quantify Sources of Settling Particles in Lakes: Resuspension Versus New Sedimentation of Material From Planktonic Production. Marine and Freshwater Research 46:223-231.
Womble, R.N., C.T. Driscoll, and S.W. Effler. 1996. Calcium Carbonate Deposition in Ca2+ Polluted Onondaga Lake, New York, U.S.A. Water Research 30(9):2139-2147.
Yin, C. and D.L. Johnson, 1984. An Individual Particle Analysis and Budget Study of Onondaga Lake Sediments. Limnology and Oceanography 29:1193-1201.