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Gradients and Dynamics in Downward Flux and Settling Velocity in Cannonsville Reservoir[1]

S. W. Effler and C. M. Brooks
Upstate Freshwater Institute
P.O. Box 506
Syracuse, NY 13214

ABSTRACT

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Seasonal and longitudinal patterns in downward fluxes and settling velocities of selected particulate constituents, including suspended solids (TSS), organic carbon (C), nitrogen (N), phosphorus (P) and chlorophyll (C_T), are documented for eutrophic Cannonsville Reservoir, NY, for the stratification period of 1995, based on analyses of particulate concentrations in the epilimnion and sediment collected in cylindrical traps deployed below the epilimnion at six different sites. Strong longitudinal gradients in downward flux were observed for all the constituents; the highest rates prevailed in the upstream/riverine zone, the lowest in the downstream/lacustrine zone. These gradients in deposition were driven by gradients of the same form in both the concentrations of the particulate constituents in the epilimnion and the settling velocities of these materials. Substantial temporal variability was observed in particulate species concentrations, and the downward fluxes and settling velocities of these constituents. The mean settling velocities of C_T, particulate organic C, P, and TSS for the lacustrine zone of the reservoir were 0.17, 0.32, 0.88, and 0.73 $m \cdot d^{-1}$, respectively. The distinctly higher values for TSS, organic C, and P, compared to C_T, reflect contributions to deposition from non-phytoplankton particles, probably associated with sediment resuspension processes and allochthonous inputs. The fluxes and settling velocities reported here are important in supporting the development and testing of related water quality models for the reservoir.

Key Words: deposition, downward flux, settling velocity, particles, particulates, sediment traps, resuspension.

Deposition is the major pathway by which particles are removed from the water column of lakes and reservoirs. Non-conservative materials, many of ecological and water quality significance, become associated with, or incorporated in, these particles. Quantification of downward fluxes (units of $g \cdot m^{-2} \cdot d^{-1}$) and settling velocities (units of $m \cdot d^{-1}$) is fundamental to understanding and quantifying the cycling of these constituents (e.g., Evans and Hakanson 1992, Rosa et al. 1991). For example, the rate of deposition expressed as a settling velocity is a key parameter in many mechanistic models intended to simulate the behavior and concentrations of environmentally important materials (e.g., Bloesch and Sturm 1986, Chapra and Reckhow 1983, Doerr et al. 1996, Thomann and Mueller 1987). Despite this, these important model inputs are rarely supported by direct measurement, but rather selected from compilations of literature values (e.g., Bowie et al. 1985) that are instead the result of model calibration (see Thomann and Mueller 1987).

Net sedimentation can be assessed through sediment dating techniques (Krishnaswami and Lal 1978) or long-term budget calculations (e.g., Dillon et al. 1990, Edmondson and Lehman 1981). The temporal resolution of these approaches is too coarse for certain applications (e.g., to support seasonal simulations of the distribution of phytoplankton and nutrients), and recycle pathways of deposited particles, including resuspension (Bloesch 1995), cannot be assessed. Properly designed sediment traps (e.g., Bloesch and Burns 1980, Hargrave and Burns 1979, Rosa et al. 1991) can be used to assess the downward flux of particulate constituents with much finer temporal resolution, and to delineate recycle pathways of these materials (Bloesch 1995, Dillon et al. 1990).

The rate of sedimentation of particles, as determined with sediment traps, is the result of deposition of new particles reaching the system (from allochthonous and autochthonous origins) and the redeposition

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of particles resuspended (i.e., old) from the lake or reservoir bottom (Bloesch 1995, Evans 1994, Evans and Hakanson 1992). Sinking flux is regulated by the concentration or standing crop of particles, as well as by particle characteristics such as size, shape, and density, and ambient physical and chemical characteristics (Hutchinson 1957, Weilenmann et al. 1989). The effects of the latter influences (i.e., other than particle concentration) can be parameterized by settling velocity. Watercolumn concentrations of various particulate constituents are routinely measured, and downward fluxes have been increasingly reported in the sediment trap literature (e.g., see review of Rosa et al. 1991). However, field estimates of sinking velocities have only rarely been reported (e.g., Baines and Pace 1994, Bloesch and Sturm 1986, Callieri et al. 1991, Effler et al. 1998a, Wodka et al. 1985).

A sediment trap positioned just below the epilimnion (e.g., upper portion of the hypolimnion) measures the net downward flux out of this layer and the gross downward flux into the hypolimnion. Delineation of deposition rate(s) at this position in the water column is consistent with the vertical segmentation of important processes, such as primary production, as well as the framework of mechanistic models designed to simulate these processes (e.g., Canale et al. 1996, Doerr et al. 1996, 1998). Downward fluxes in many lakes can be assessed with a sediment trap(s) deployed at a single central location (e.g., Bloesch and Uehlinger 1986, Effler and Brooks 1997). Rarely are spatial gradients in suspended particle concentrations observed within the pelagic region of lakes, even where sediment resuspension within the epilimnion contributes substantially to downward flux (Evans 1994). This is not the case for reservoirs associated with the transition from a lotic to a lacustrine environment where substantial gradients in particle concentrations and characteristics often prevail (James et al. 1987). These gradients can be expected to have both an allochthonous (greater particle carrying capacity of lotic system associated with higher levels of turbulence) and an autochthonous (phytoplankton biomass gradient in response to gradients in nutrient availability) component. Thus, longitudinal differences in downward flux are to be expected, associated with spatial differences in particle concentrations and characteristics (e.g., settling velocity).

Here we document the seasonal dynamics and longitudinal pattern of downward flux of suspended solids (dry weight), organic carbon (C), nitrogen (N), phosphorus (P), and chlorophyll (C_T) in Cannonsville Reservoir, NY. Paired patterns of epilimnetic concentrations of the particulate species and calculated settling velocities of these constituents are presented as well. The dynamics, spatial heterogeneity, and stoichiometry of the deposition of these materials are analyzed within the context of the roles of allochthonous inputs and autochthonous processes. Findings of this study, and other sediment trap results (not reported here), support an analysis of resuspension (Effler et al. 1998b) and the development and testing of a water quality model (Doerr et al. 1998) for the reservoir, presented elsewhere in this issue.

Methods

System

Cannonsville Reservoir, NY, is a large (crest capacity of 373 x 10^6 m^3; mean depth, when full, of ~ 19 m), eutrophic (Effler and Bader 1998) reservoir located about 120 miles (~ 190 km) northwest of New York City. The principal axis of the reservoir corresponds to the riverbed of the West Branch of the Delaware River (WBDR), the other smaller arm is associated with Trout Creek (Fig. 1). Gradients in a number of water quality parameters commonly prevail along the principal axis (Effler and Bader 1998). The reservoir is used primarily to maintain flows in downstream portions of the Delaware River and as a water supply for the city. Substantial drawdown of the reservoir has been experienced in many years (Owens et al. 1998). A major drawdown was experienced in the summer of 1995 (Owens et al. 1998); the reservoir was at about 44% capacity by the beginning of September. Detailed descriptions of the reservoir's morphometry, hydrology, operation (Owens et al. 1998), limnology (Effler and Bader 1998), and watershed (Longabucco and Rafferty 1998) have been presented in previous manuscripts of this issue of the journal. Owens (1998) described transport processes in the reservoir for the spring-fall

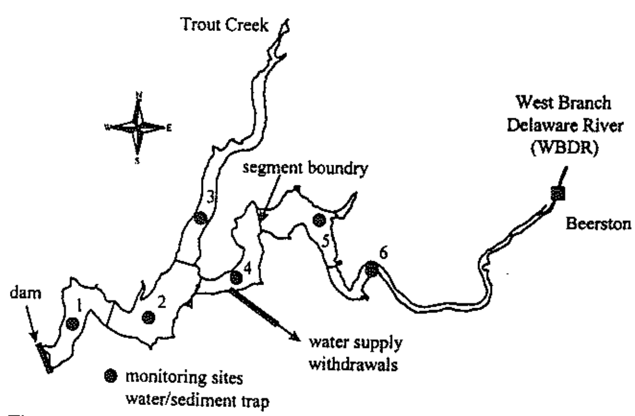

Figure 1.–Cannonsville Reservoir map, with watercolumn and sediment trap sampling locations for 1995 study.

interval of 1995. Interflows of WBDR were indicated irregularly in the mid-June to mid-August interval, and WBDR entered as an underflow after mid-August.

Sediment Trap Program

Trap design followed the unifying recommendations of several investigators (Bloesch and Burns 1980, Blomqvist and Hakanson 1981, Hargrave and Burns 1979, Rosa et al. 1991). The traps were cylindrical PVC tubes with an aspect ratio (height/diameter) of 6. The diameter of the traps was 7.6 cm. Traps were suspended vertically supported by air-filled polyethylene containers (e.g., Wodka et al. 1985; so as not to reduce the effective area of the orifices exposed to the depositing material) at six sites (Fig. 1), corresponding to water quality monitoring positions and representative of the range of lacustrine and riverine zones of the reservoir (Effler and Bader 1998). Sites 1, 2, 4, 5, and 6 extended along the main (WBDR) axis of the reservoir; site 3 was located in the Trout Creek arm (Fig. 1). The details of trap design, deployment, collection, and handling correspond to those utilized in deposition studies on Onondaga Lake (Effler and Brooks 1997, Effler et al. 1998a, Womble et al. 1996). Traps were deployed continuously over the April-October period of 1995 and collected weekly, a frequency that is expected to minimize the effects of minerialization on measured downward fluxes (e.g., Rosa et al. 1991). Initially, the traps were deployed approximately 8 m below the surface, to reflect net deposition into the hypolimnion from the epilimnion, consistent with the intention to support related water quality modeling efforts for the reservoir [e.g., Doerr et al. 1998, also see Doerr et al. (1996) and Canale et al. (1996) for similar applications of trap studies for water quality models]. Readjustment (vertical) of the deployments (see Wodka et al. 1985) was necessary as reservoir drawdown proceeded (Effler and Bader 1998, Owens et al. 1998) to keep the traps below the upper mixed layer of the reservoir. These traps remained above the hypolimnetic depths influenced by "bottom resuspension" throughout the stratification period (Effler et al. 1998b). Additionally, collections were made at the weekly frequency for a sediment trap deployed 3 m above the sediment-water interface at site 4 (Figure 1). Fluxes determined from these collections, as well as those made after the onset of fall turnover at all depths, are included in the analysis of resuspension in the reservoir presented by Effler et al. (1998b).

Resuspension of particles collected in the traps is unlikely based on the findings of Lau (1979); a horizontal velocity of ~ 24 cm · s^{-1} would have been necessary proximate to the trap orifice to induce resuspension of material from the traps. Further, there was no visual evidence of loss of material during retrieval of the traps; the traps always contained relatively transparent water overlying the deposited particles material.

Aliquots for trap collections analysis were taken from homogenized samples. The aliquot for organic C and N analyses was filtered through a 1.5-µm pore size glass fiber filter, dried (103 °C), and weighted. Carbon and N analyses were conducted with a Carlo Erba Model EQ1108 elemental analyzer. Separate aliquots were analyzed for total phosphorus (TP); (APHA 1992), total suspended solids (TSS); (APHA 1992), and total chlorophyll (C_T; summation of chlorophyll *a*, *b*, and *c*); (Parsons et al. 1984).

The downward fluxes (DFs) of TSS, organic C, N, P, and C_T are represented as areal rates (e.g., units of mg · m^{-2} · d^{-1}). The fluxes were determined for each individual deployment period and site from the mass of the constituent collected in the trap (W; g), the sediment trap deployment period (T; 7d), and the area of the trap opening (A; m^2), according to the relationship

$$DF = W/(A \cdot T) \qquad (1)$$

Settling velocity (SV) was estimated for each constituent, individual deployment period, and site, according to

$$SV = DF/PC \qquad (2)$$

where PC is the particulate concentration of each constituent in the epilimnion (e.g., above the traps, mg · m^{-3}). The value of PC was determined as the average concentration over the 0- to 6-m-depth interval [consistent with the dimensions of the epilimnion (e.g., Gelda et al. 1998)], based on profiles (2) measured on the days of deployment and collection (also see Wodka et al. 1985).

Water Column Program

Water column concentrations of TSS, particulate organic C (POC), C_T, TP and total dissolved (0.45 µm) P (TDP), (APHA 1992) were measured at depths of 0, 3 and 6 m, at each site (except when site 6 became too shallow), on the days of deployment and collection throughout the study period. Particulate P (PP) was calculated as the residual of TP and TDP. These values of PP matched reasonably well determinations of PP made on particles collected on filters (0.45 µm), conducted on a subset of samples (n = 69, average 18% difference). Analyses of POC were conducted as described for the trap collections.

Particle size analyses were performed on samples from a depth of 3 m on June 27 (sites 1, 4, and 5) and August 29 (sites 1, 4, 5, and 6), with a HIAC/ROYCO Model 8000A particle counter. Particle size ranges measured in these analyses were 1.5 to 2.5, 2.5 to 5.0, 5.0 to 7.5, 7.5 to 10.0, 10 to 12.5, 12.5 to 15, 15 to 20 and > 20 µm.

Results and Discussion

Watercolumn Particulate Concentrations

Wide variations in the concentrations of TSS, POC, PP, and C_T occurred throughout the epilimnion of the reservoir during the study period (e.g., Fig. 2). Variations in TSS, POC, and PP were largely uncoupled from the dynamics of C_T in the upper waters of the reservoir for much of the study period (e.g., Fig. 2), indicating other significant sources (e.g., allochthonous, resuspension) contribute to the pools of these materials. Systematic longitudinal differences were also evident, particularly from mid-to-late summer. For example, concentrations were substantially higher at site 5 than at site 1 for much of the study (Fig. 2); on average, concentrations at site 5 were 70, 24, 43, and 15% higher for TSS, POC, PP, and C_T, respectively. Progressive decreases in average concentrations were observed along the WBDR axis from site 6 to site 4, and remained largely unchanged further downstream (toward the dam, Fig. 3). Concentrations at site 3 were similar to those measured at sites 1, 2, and 4 (Fig. 3). The structure of these longitudinal gradients [C_T gradient reported previously by Effler and Bader (1998)] is consistent with Effler and Bader's (1998) description of sites 1 to 4 as lacustrine, site 5 as a transition zone, and site 6 as riverine [see Kimmel and Groeger (1984) for description of zone classification system]. Temporal variability (represented by ± 1 standard deviation bars in Fig. 3) was generally greater at the upstream stations, reflecting variations in riverine (allochthonous) particulate inputs. Dynamics in the effective depth of entry of WBDR (Owens 1998) may have contributed to the variations, particularly at sites 5 and 6.

Downward Fluxes

Time series of DFs are presented here for all the sites for TSS (Fig. 4) and C_T (Fig. 5) to depict temporal structure. In light of the level of precision established for trap collections in general [e.g., coefficient of variation (cv) of ~ 10%] (Rosa et al. 1991), and for the specific configuration and protocols adopted here (Effler and Brooks 1997, Effler et al. 1998a, Womble et al. 1996), substantial seasonal variations occurred in the lacustrine zone (Figs. 4 and 5) and abrupt short-term differences in TSS deposition were common at the riverine site (Fig. 4f). The irregular occurrence of interflows from WBDR may have influenced the patterns at sites 5 and 6 after mid-June. Basically the same

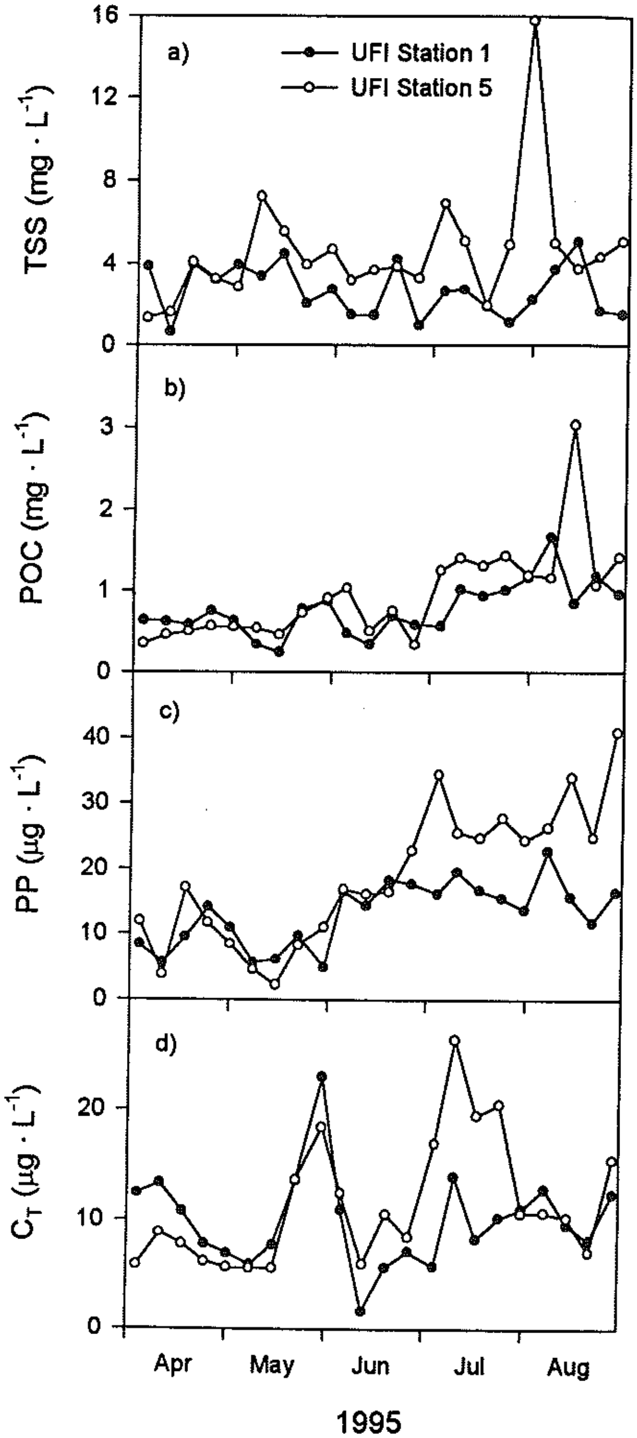

Figure 2.–Time series of epilimnetic concentrations of particulate constituents in Cannonsville Reservoir for the April-September interval of 1995, at sites 1 and 5: a) TSS, b) POC, c) PP, and d) C_T.

seasonality was observed for all the lacustrine sites. A generally decreasing trend in the DF of TSS was observed over the April to early June interval in the lacustrine and transition zones of the reservoir (Fig. 4a-e). The low TSS fluxes of June coincided with low deposition of C_T (Fig. 5a-c) and the minimum of phytoplankton biomass observed for the epilimnion of the reservoir

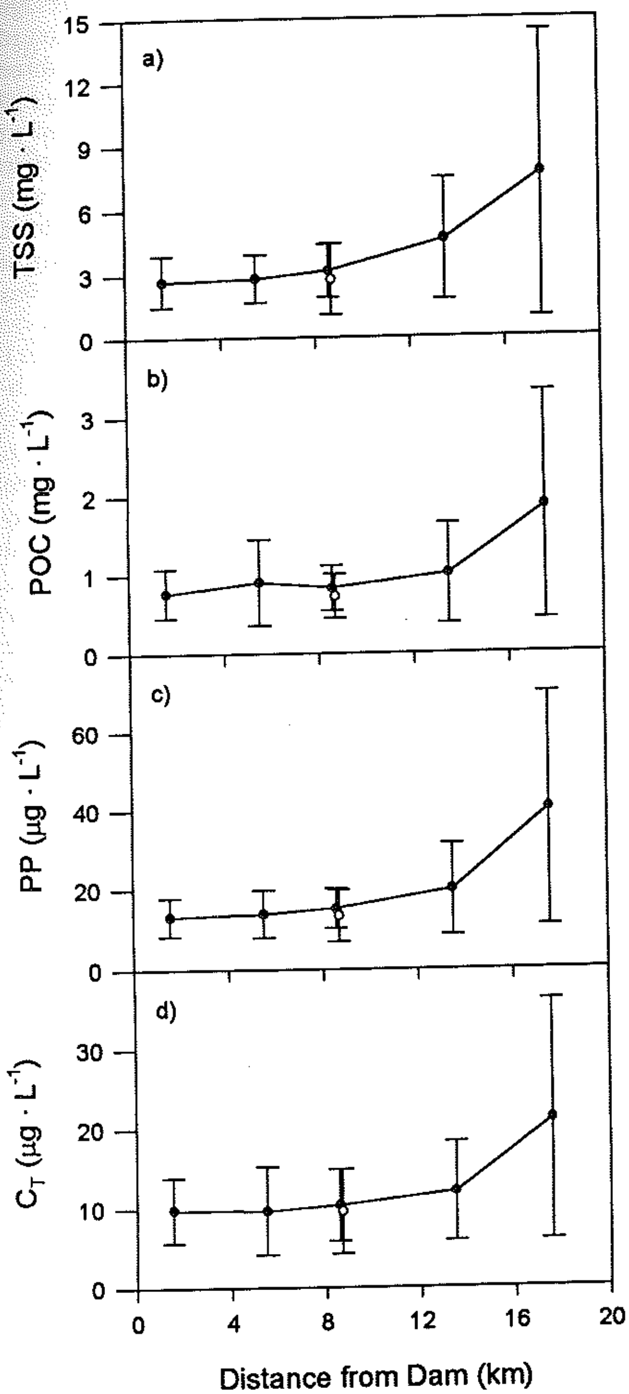

Figure 3.–Longitudinal profiles of study average concentrations of particulate constituents in Cannonsville Reservoir for the April-September interval of 1995: a) TSS, b) POC, c) PP, and d) C_T. Bars correspond to ± 1 standard deviation.

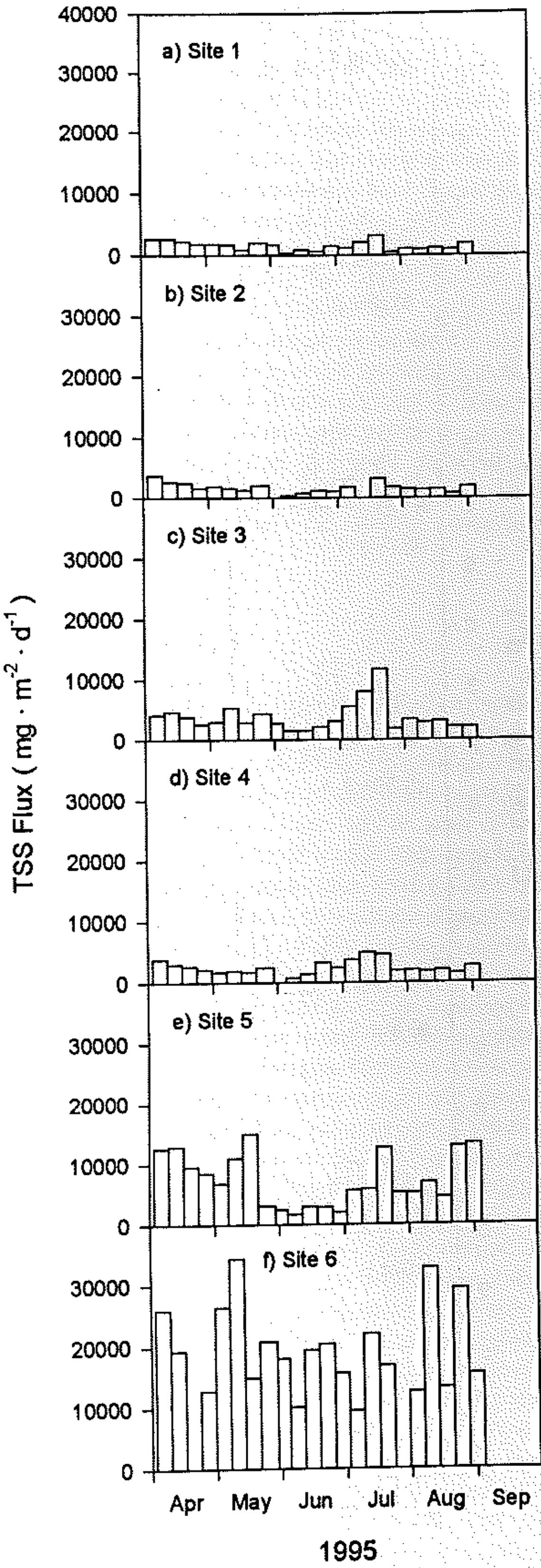

Figure 4.–Time series of the downward flux (DF) of TSS in Cannonsville Reservoir for the April-September interval of 1995: a) site 1, b) site 2, c) site 3, d) site 4, e) site 5, and f) site 6.

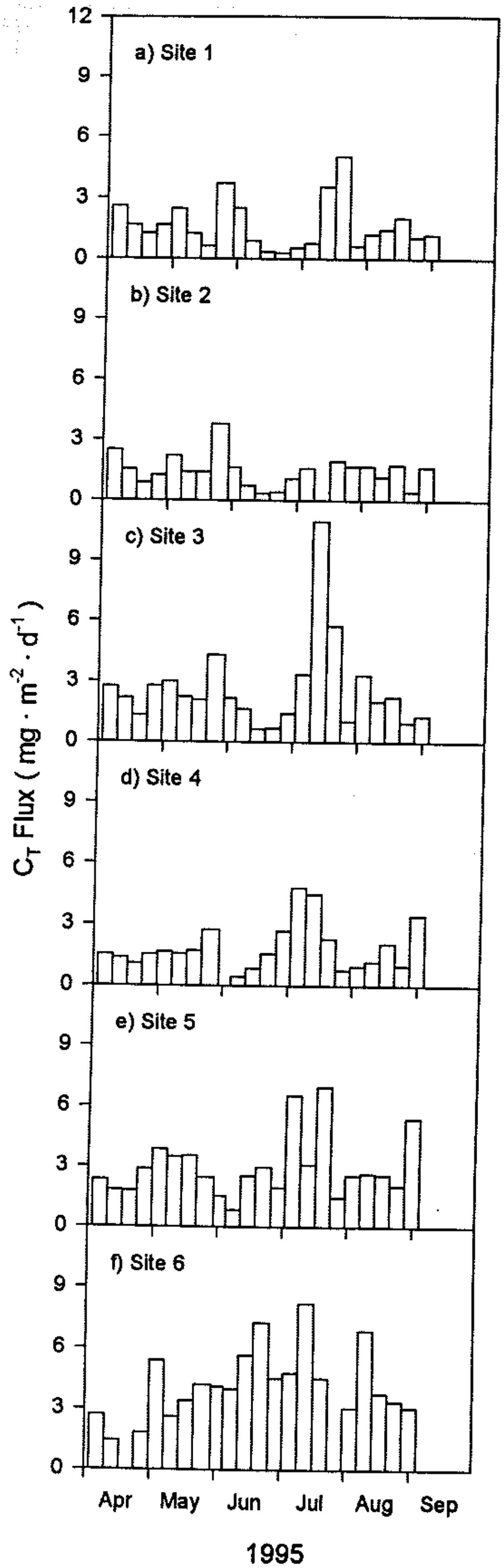

Figure 5.–Time series of the downward flux (DF) of C_T in Cannonsville Reservoir for the April-September interval of 1995: a) site 1, b) site 2, c) site 3, d) site 4, e) site 5, and f) site 6.

(Fig. 2d). Subsequent increases in the TSS flux developed through mid-July (Fig. 4a-e), again coincident with peak C_T deposition (Fig. 5a-e).

Longitudinal gradients in the DFs of TSS and C_T along the main axis of the reservoir are apparent from comparative review of the temporal distributions (Figs. 4 and 5). Gradients emerge for all five constituents in review of the longitudinal profile of the study average fluxes (Fig. 6a-e). James et al. (1987) also found gradients in deposition prevailed (based on three longitudinal sites) for TSS, organic C, and chlorophyll along the axis of DeGray Lake (reservoir; deployment period of 2 wk, aspect ratio of 3). The gradients in Cannonsville Reservoir are generally consistent with those observed for the concentrations of these constituents in the epilimnion (Fig. 3). The strongest gradient in deposition along the WBDR axis was observed for TSS (Fig. 6a), the average DF at site 6 was 19.5 g · m^{-2} · d^{-1}, about 12.5X greater than at site 1 (1.55 g · m^{-2} · d^{-1}). This structure largely reflects allochthonous inputs (e.g., Longabucco and Rafferty 1997), as well as resuspension from the shallow upstream portions of the reservoir bottom during drawdown (Effler et al. 1998b). The absolute temporal variability (± 1 standard deviation bars, Fig. 6) decreased progressively from the riverine site towards the dam, though the relative variabilities (cv) were rather similar (0.35 to 0.6) over the length of the reservoir. The smallest longitudinal gradient in deposition was observed for C_T, the ratio of the average fluxes measured at sites 6 and 1 was about 2.5 (Fig. 6e). The ratios for organic C, N, and P DFs for these two sites were about 4.8, 4.0, and 6.7, respectively. Deposition rates of TSS and P at site 3 were about 1.5 and 1.4X greater than observed for site 4, presumably reflecting higher allochthonous contributions associated with the greater proximity of this site to the mouth of an inflow (Fig. 1).

The lacustrine fluxes of TSS in Cannonsville Reservoir (Fig. 6a) fall within the upper portion of the range reported for lakes [review by Effler and Brooks (1997)]. The riverine flux is at the upper bound for lakes (e.g., Effler and Brooks 1997, Rosa et al. 1991), but in light of the very high net sedimentation rates reported for certain reservoirs (e.g., Ritchie et al. 1973) and the DFs reported for DeGray Lake (James et al. 1987), it is not expected to be a particularly high deposition rate for reservoirs. Compilations for deposition rates of the other constituents are much smaller (e.g., Effler et al. 1996). The lacustrine fluxes of organic C (Fig. 6b) fall within the lower portion of the range reported for selected eutrophic lakes [n = 11, reviewed by Effler et al. (1996)], and near the median of observations reported for 15 lakes in Northeastern United States described as representing a wide range of trophic state (Baines and Pace 1994). The flux(es) in

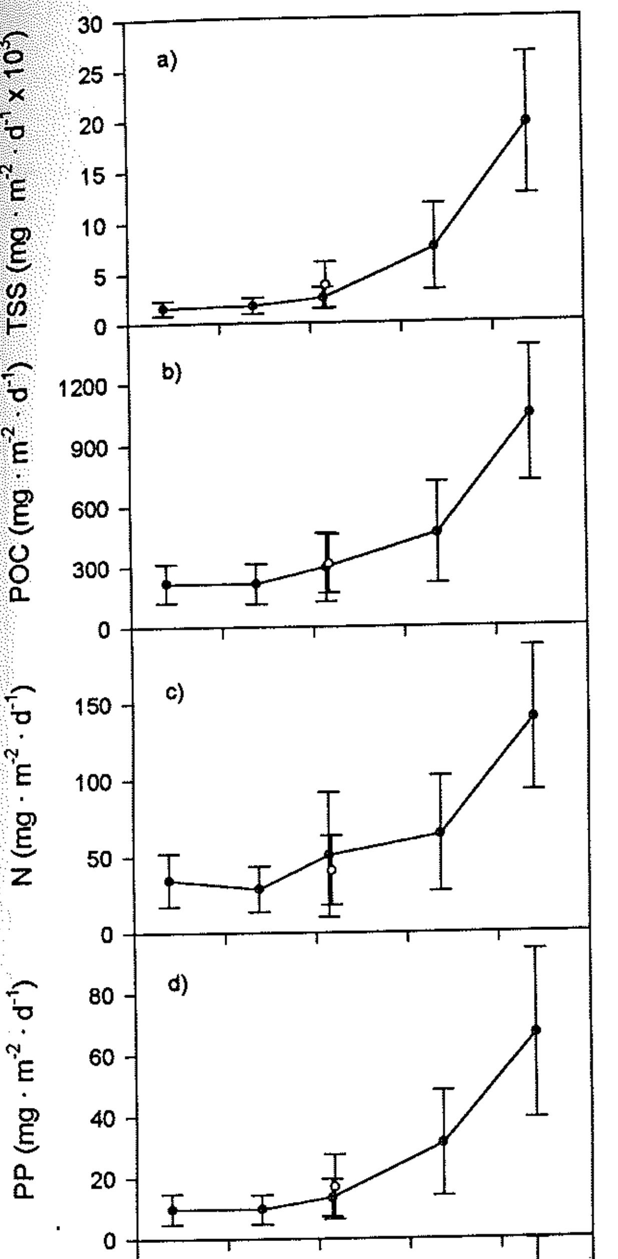

Figure 6.–Longitudinal profiles of study average downward fluxes (DFs) of particulate constituents in Cannonsville Reservoir for the April-September interval of 1995: a) TSS, b) organic C, c) N, d) P, and e) C_T. Bars correspond to ± 1 standard deviation.

the riverine zone approaches the upper bound presented by Effler et al. (1996) and exceeds the highest value reported by Baines and Pace (1994). Though the flux of organic C has been adopted as an indicator of trophic state by some investigators (e.g., Kelly and Chynoweth 1981), this use is compromised (e.g., phytoplankton biomass is not the only component of organic C) for the riverine zone, and to a lesser extent in other portions of the reservoir (see subsequent findings and discussion), by contributions from resuspension (Effler et al. 1998b) and allothonous sources. The N and C_T fluxes of the lacustrine zone are well within the bounds reported by Baines and Pace (1994). The lacustrine P fluxes are high compared to values reported for lakes in the literature (e.g., Baines and Pace 1994, Wodka et al. 1985). Allochthonous inputs and resuspension (subsequently in this manuscript; also see Effler et al. 1998b) contribute to the fluxes of N and P.

Settling Velocities

The dynamics of the calculated settling velocities (SVs) that correspond to the trap deployment intervals are illustrated here for TSS, POC, PP, and C_T, for site 4 (Fig. 7a-d). A high degree of temporal variability is indicated. Baines and Pace (1994) also observed substantial temporal variability in SV values calculated from sediment trap studies. No doubt some of the variability is an artifact of the limitations of assumptions inherent in the calculations. For example, the averaging of particulate concentrations from the days of deployment and collection of the traps is an imperfect representation of the true average concentrations of these particles above the traps. Further, collection of depositing particles necessarily lags the period of averaging of watercolumn concentrations because of the vertical distance between the epilimnion and the deployment depth. These effects are difficult to quantify, but are considered modest; i.e., substantial temporal variability in the SVs of these materials occurred. These estimates of SV incorporate the entire assemblage of components (e.g., sizes, chemical types) that contributed to the water column concentrations of each constituent, and undoubtedly represent a composite of different settling velocities of the array of particles. Variations in SV could be associated with either the autochthonous, allochthonous, or resuspended components (or combinations of these components). Allocthonous inputs of TSS to the reservoir are relatively enriched in the inorganic (i.e., dense with high SV) fraction. However, dynamics in tributary inputs of particles are an unlikely source of variations in the SVs (particularly TSS, POC, N, and

PP), as flows remained low and concentrations rather uniform throughout the study period (Longabucco and Rafferty 1998). Variation in the quantity, composition, and physiological state of phytoplankton (i.e., autochthonous component; Bowie et al. 1985) is doubtless a contributor to the observed dynamics in SV [e.g., Fig. 7 (also see Effler et al. 1996)]. Variations in response to the irregular input of resuspended sediments (e.g., resuspended from wave action on shore, e.g., Bloesch 1995, Evans 1994) associated with natural variability in meteorological forcing conditions and the progression of drawdown is also a reasonable expectation.

The same general longitudinal structure in average SVs emerges for Cannonsville Reservoir (Fig. 8) as documented for particle concentrations (Fig. 3) and DFs (Fig. 6): decreasing values from the riverine to the lacustrine zones and rather uniform conditions within the lacustrine zone. These findings are quite important in understanding the observed gradients in DFs in this system (Fig. 6) and almost certainly many other reservoirs. The DFs of the riverine and transitional zones are a result of both greater particulate concentrations and higher SVs (i.e., different settling characteristics). The point is perhaps somewhat intuitive, but to our knowledge not previously demonstrated at the time scale of sediment trap studies. These findings are consistent with the particle count/size data available for the main axis of the lake in late June and August of the study period (Table 1). Three important features emerge from the particle data (Table 1): (1) a clear gradient in the concentration of particles occurred (e.g., particulate species concentrations), (2) a clear gradient in the concentration of larger (> 10 μm) particles occurred (i.e., tendency for more rapid deposition), and (3) concentrations of particles of all the measured size classes were greater for the August sampling. These particle size/count data are generally consistent with the larger population of measurements, based on electron microscopy, included in the analysis of sediment resuspension (Effler et al. 1998b). The higher concentrations for the August date (Table 1) are at least in part due to increases in inorganic particles associated with resuspension (Effler et al. 1998b). The strongest gradient in SV was found for TSS; the ratio of the average values was about 5. Much of this gradient can be attributed to the selective removal of the larger more dense allochthonous or resuspended particles within the riverine and transition zones. The smallest gradient (1.7) was for C_T. The modest differences for C_T (greatest in April and May) most probably reflect differences in phytoplankton composition; e.g., riverine diatoms tend to be larger (e.g., Hynes 1970) and may preferentially settle out in the upper portions of the reservoir.

It is valuable to compare the SVs determined here for the different constituents (Table 2) to values reported elsewhere. Baines and Pace (1994) observed no systematic difference in the SVs of POC, N, and phytoplankton pigments for individual lakes included in their study of 15 lakes. Callieri et al. (1991) also

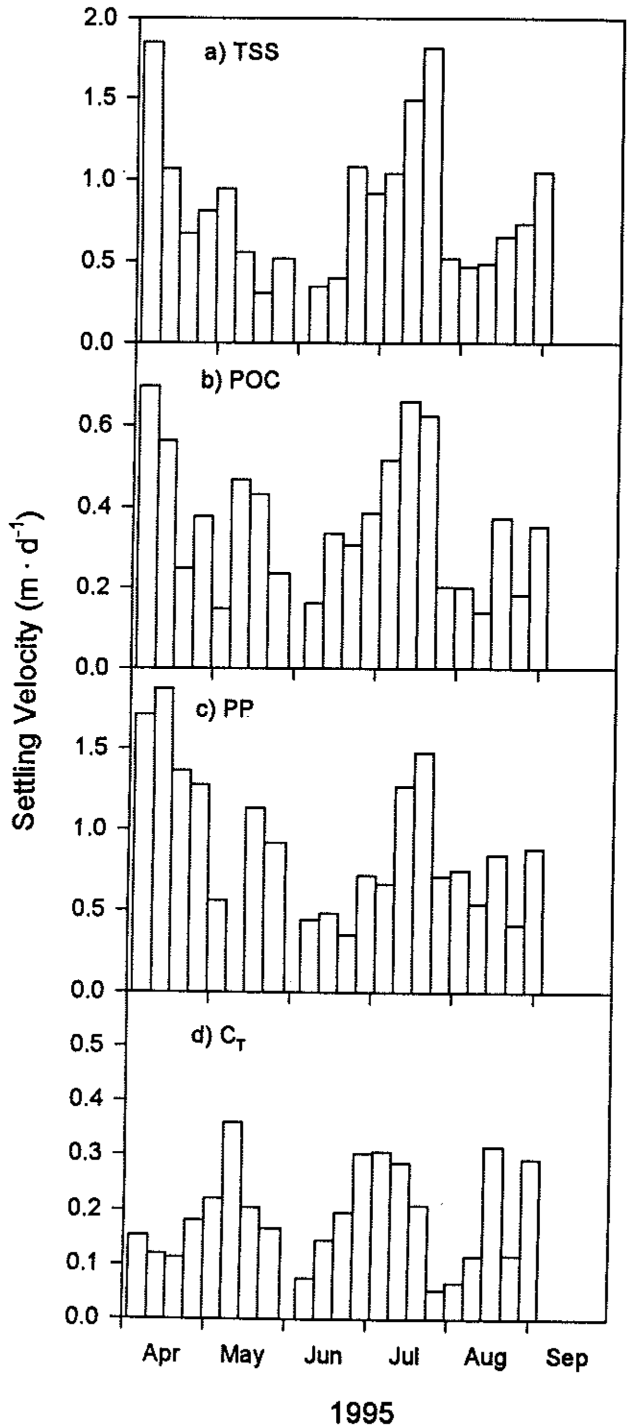

Figure 7.–Time series of estimated settling velocities (SVs) of particulate constituents in Cannonsville Reservoir, at site 4, for the April-September interval of 1995: a) TSS, b) POC, c) PP, and d) C_T.

found the POC and chlorophyll SVs to be similar in Lago de Mergozzo (Italy). These findings reflect common origins of these constituents in phytoplankton biomass (i.e., no significant non-phytoplankton sources of the materials). The average SV of C_T for the lacustrine portion of Cannonsville Reservoir (Table 2) falls well within the range observed by Baines and Pace (1994; 0.04-0.66 m · d^{-1}). The distinctly higher SV values determined for POC and P in the reservoir (Table 2) reflect contributions of these constituents from non-phytoplankton particles that settle more rapidly than the phytoplankton. Effler et al. (1998b) have attributed the non-phytoplankton particles largely to resuspension. The resuspended sediments are predominantly inorganic (> 90%), composed mostly of quartz and clays (Effler et al. 1998b). The resuspended organic component apparently is responsible for making the overall aggregate (e.g., mix of resuspended organic and phytoplankton) average POC SV of the lacustrine zone nearly twice as high as the C_T value (Table 2). The yet higher SV for TSS (Table 2) reflects the substantial contribution inorganic (e.g., more dense) particles make to the particle population of the reservoir epilimnion.

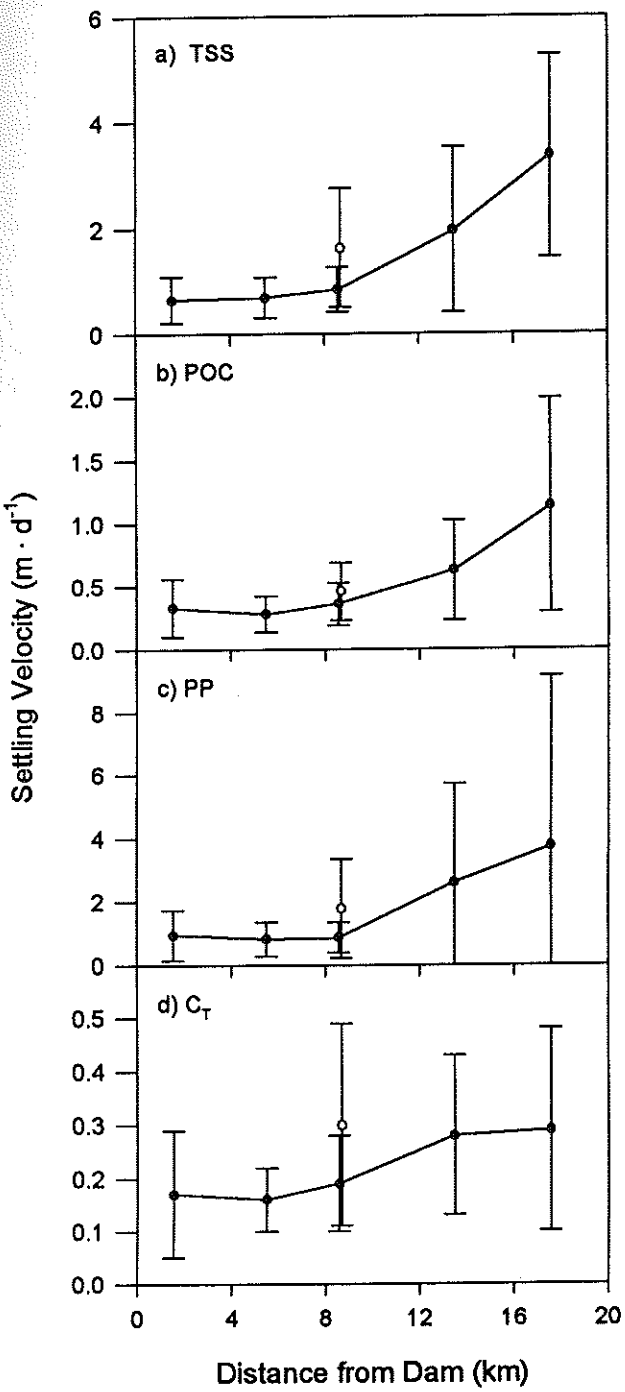

Figure 8.–Longitudinal profiles of study average settling velocities (SVs) of particulate constituents in Cannonsville Reservoir for the April-September interval of 1995: a) TSS, b) POC, c) PP, and d) C_T. Bars correspond to ± 1 standard deviation.

Effler and Bader (1998) reported that on average about 40% of TSS in the reservoir's epilimnion over the 1989-1995 interval was nonvolatile (i.e., inorganic). Approximately 70% of the TSS flux over the study period of 1995 was inorganic at site 4 (Effler et al. 1998b). Applying these percentages to the average TSS concentration and downward flux for site 4, we calculate an average SV of about 1.4 m · d^{-1} for inorganic TSS in the reservoir. This is very close to the average (~ 1.3 m · d^{-1}, for eight deployment intervals) estimates from observations reported by Callieri et al. (1991) for Lago de Mergozzo. Combined particle chemistry and size distribution data presented by Effler et al. (1998b) indicate this value almost certainly varies with time (e.g., Callieri 1991) because of shifts in particle size which apparently are linked to drawdown of the reservoir. The above estimate of the SV of inorganic TSS in the reservoir is supported by closure of the volatile TSS SV estimate (0.4 m · d^{-1}; calculated in the same manner as for the inorganic fraction) with that determined as the study average for POC at site 4 (Table 2). The high SV for inorganic TSS is attributable to the greater density of inorganic particles compared to organic particles (e.g., Weilenman et al. 1989). This

Table 1.–Particle count/size data for Cannonsville Reservoir for two selected dates in 1995, at a depth of 3 m.

Site	Particle Counts · ml^{-1}			
	June 27		August 29	
	Total	> 10 μm	Total	> 10 μm
1	14,500	173	15,600	409
4	18,300	302	28,000	999
5	28,200	635	55,400	2429
6			212,700	2396

Table 2.–Average settling velocities in Cannonsville Reservoir for the April-August interval of 1995.

Site	Zone Type	Settling Velocity ($m \cdot d^{-1}$) TSS	POC	PP	C_T
6	riverine	3.35	1.14	3.75	0.29
5	transition	1.95	0.63	2.61	0.28
4	lacustrine	0.84	0.36	0.87	0.19
3	lacustrine	1.62	0.46	1.78	0.30
2	lacustrine	0.69	0.28	0.82	0.16
1	lacustrine	0.65	0.33	0.94	0.17
	avg. lacustrine+	0.73	0.32	0.88	0.17

+ average for sites 1, 2, and 4

effect is largely responsible for the high value of the TSS SV relative to the values for POC and C_T. The lacustrine zone SV for PP was somewhat greater than the TSS value (Table 2; though the site 4 values are essentially equal), indicating the inorganic particles of the epilimnion were enriched in P relative to the organic particles. Clays are known to have a high absorption capacity for P (Böstrom et al. 1988).

Stoichiometry of Fluxes

The composition of suspended seston (as ratios), with respect to organic C, N, P, and chlorophyll, has been used to assess the nutrient status of phytoplankton in lakes (Healey and Hendzel 1980, Hecky et al. 1993). This approach has been extended to the composition of depositing seston (Effler et al. 1998a), acknowledging that short-term diagenetic processes may cause modest changes in these signatures over the interval of deposition and trap deployment (e.g., 1 to 20 d, see Table 2). Contributions from non-phytoplankton particles, as suggested by results presented here (e.g., Table 2, Fig. 8) and elsewhere in this issue of the journal, compromise application of this approach to assess the nutrient status of the phytoplankton (see Hecky et al. 1993) of this reservoir. However, review of the spatial differences in ratios of the fluxes of the these materials (Table 3) yield valuable insights concerning their origins, and comparison to the limits set by Healey and Hendzel (1980) for nutrient deficiency/sufficiency serves to illustrate the nature of the interference from non-phytoplankton particles.

All the ratios considered (Table 3) were significantly different ($p < 0.05$) in the riverine versus the lacustrine zones of the reservoir, consistent with the heterogeneity and gradients documented for various constituents [e.g., Fig. 3, also see Effler and Bader (1998)] and processes (e.g., Fig. 8). The stoichiometry of particles in the riverine zone was more temporally uniform than for the lacustrine zone. The depositing particles in the lacustrine zone were enriched in N and C_T relative to

Table 3.–Indicator values (as ratios*) of nutrient sufficiency and deficiency for phytoplankton growth (Healey and Hendzel 1980), and ratio for depositing seston for riverine and lacustrine locations in Cannonsville Reservoir, NY.

Ratio	Nutrient(s)	Sufficiency**	Deficiency**	Riverine	Lacustrine++
POC:N	N	< 7.1	> 12.5	7.6 (0.13)+	6.2 (0.21)
N:PP	P	< 10	> 10	2.3 (0.32)	3.8 (0.44)
POC:PP	P	< 50	> 100	16.8 (0.27)	22.5 (0.32)
POC:C_T	General	< 50	> 100	272 (0.38)	176 (0.43)
C_T:PP	-			0.070 (0.49)	0.16 (0.72)

* $mg \cdot mg^{-1}$
** values intermediate between sufficiency and deficiency described as moderately deficient (Healey and Hendzel 1980)
+ coefficient of variation (cv)
++ site 4

organic C, with diminished P relative to N and organic C, compared to the riverine zone (Table 3). The most temporally uniform ratio was for organic C:N (Table 3), a widely observed condition for seston of both autochthonous and allochthonous origins (Hecky et al. 1993). The ratio values indicate essentially N sufficient conditions for phytoplankton growth (Table 3). This compromised indicator is misleading as it is contrary to the distinct N-limiting conditions that prevailed in the reservoir in late summer and early fall (Effler and Bader 1998). Similarly, the contributions of resuspension and allochthonous inputs to reservoir deposition compromise the other stoichiometric ratios (Table 3) as indicators of the nutrient status of phytoplankton. The low N:PP and POC:PP ratios of the trap collections (Table 3) indicate an extremely high degree of sufficiency of P, that is inconsistent with the distinctly P-limiting conditions observed for much of the study (Auer 1998, Doerr et al. 1998). Further, the extremely high POC:C_T ratio in the traps indicate severe overall nutrient deficiency (Table 3), which is at odds with all the other nutrient status indicators. The C_T:PP ratios for both zones are much lower than found for phytoplankton (usually 1:2; Bowie et al. 1985), indicating non-phytoplankton particulate P dominated depositing P during the study.

Management Summary

This program of analyses of sediment trap collections and particulate species concentrations has documented the magnitudes and gradients in downward flux, particulate concentrations, and settling velocity of several constituents of water quality concern for Cannonsville Reservoir. The gradient in downward flux, with the highest deposition occurring in the riverine zone and the lowest in the lacustrine zone, has been established here to be a result of gradients of the same form in the concentrations of the particulate constituents as well as the settling velocities of these materials. The character of these results is expected to be respresentative of the spatial pattern of deposition in many reservoirs. Further, the results of this work are critical inputs to a water quality model for the reservoir (Doerr et al. 1998). Independent specification of the deposition pathway of these constituents is an important enhancement to the credibility of the water quality model, as the limited literature values for this process vary greatly system to system. The observed disparity in settling velocities between constituents usually associated with phytoplankton biomass indicates substantial non-phytoplankton contributions to the deposition of these materials occur, and suggests the operation of the sediment resuspension process. The findings of this study, and additional sediment trap results, are subsequently integrated into an analysis of the resuspension phenomenon in the reservoir by Effler et al. (1998b). We have also demonstrated that the non-phytoplankton component of deposition interferes with the use of sediment trap results to assess the stoichiometry, and therefore the nutrient status, of the reservoir's phytoplankton. The use of trap results to assess phytoplankton stoichiometry is probably limited to systems where resuspension does not contribute significantly to deposition from the productive layers.

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