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Sediment Resuspension in Cannonsville Reservoir[1]

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ABSTRACT

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The operation of the sediment resuspension process in Cannonsville Reservoir, NY, a eutrophic flow-augmentation and water supply impoundment for New York City, during the major drawdown year of 1995 is documented. Methodologies used in the assessment included transmissometer profiling; electron microscopy-based physical and chemical characterization of individual particles from the water column, sediments and the principal tributary; analysis of sediment trap collections; and mass balance calculations for total suspended solids (TSS). The resuspension process had several pronounced manifestations. First was the development of a conspicuous benthic nepheloid layer (BNL) which, by mid-summer, extended nearly 10 m above the bottom at one location. Second was the increase in the concentration of inorganic particles in the upper waters as the reservoir was drawn down. These particles, ultimately derived from the watershed, caused increases in turbidity. Third was the measurement of higher downward fluxes in a near-bottom sediment trap compared to a below-thermocline trap deployment and throughout the water column during the fall mixing period. Finally, the TSS deposition rate greatly exceeded estimates of TSS retention for the reservoir. The resuspension phenomenon has important management implications for this and other water supplies because it represents a source of turbidity, and because the resuspended particles interfere with widely adopted signatures of phytoplankton production. Sediment resuspension is probably promoted in this reservoir by the drawdown of the water surface.

Key Words: sediment resuspension, particles, sediment, individual particle analysis, sediment trap, mass balance, turbidity, benthic nepheloid layer, transmissometry.

Resuspension has been defined as the reconveying of particles, which have been deposited on bottom sediments, into the overlying water column (Bloesch 1995). This process occurs in response to water motion; sediment is resuspended when current-induced bottom shear stress is sufficient to overcome the cohesion of bottom sediments (i.e., sheer exceeds a critical stress necessary to mobilize particles from the bottom) and gravity. Wind is the primary driving force for the phenomenon in most lakes and reservoirs. The critical shear stress for resuspension depends on the characteristics of the sediments (e.g., Blom et al. 1992, Gloor et al. 1994). Resuspension is an ubiquitous internal process, though its relative magnitude is highly system-specific (Bloesch 1995, Evans 1994). Bloesch (1995) has identified two basic zones of resuspension

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in lakes: shallow zones that can be directly influenced by wave action and deeper areas located below the direct impact of the wave base. Currents in deep zones during periods of stratification are associated primarily with internal seiches (e.g., Bloesch 1995, Gloor et al. 1994). Increased water motion occurs irregularly at these depths in the absence of density stratification (i.e., during turnover). The setting for resuspension in reservoirs that experience substantial drawdown is more dynamic than for lakes as the sediments exposed to wave action (e.g., the shoreline) and turbulence at depth (Gelda et al. 1998) change with the lowering of the water level.

The resuspension phenomenon has broad environmental importance because of the role of suspended particles in geochemical, limnological, toxicological, and biological processes (Evans 1994). The adsorption surfaces provided can influence the cycling of phosphorus (Böstrom et al. 1988), heavy metals (Sigg et al. 1987), and toxic organics (Baker et al. 1985). Resuspended particles scatter, and to a lesser extent absorb, light (e.g., Kirk 1994, Effler et al. 1998b, Gloor et al. 1994) and thus influence clarity and light attenuation. This has implications with the respect to the public's perception of water quality (Effler 1985), the support of phytoplankton growth (Somlyody and Koncsos 1991), and the feasibility of meeting turbidity limits for water supplies. Further, the resuspension phenomenon can interfere greatly with widely applied signatures of phytoplankton production and standing crop, including: a) clarity/attenuation as a function of biomass (e.g., Effler and Perkins 1996), b) particle stoichiometry (e.g., Hecky et al. 1993), c) water column concentrations of constituents commonly associated with phytoplankton biomass (e.g., Vollenweider 1975), and d) downward fluxes and settling velocities of constituents commonly associated with phytoplankton (Effler and Brooks 1998, Effler et al. 1998a). The formation of benthic nepheloid layers, observed to varying extents in certain lakes, has also been attributed to sediment resuspension (Bloesch 1995, Gloor et al. 1994).

Though sediment resuspension has been generally acknowledged to be a widely occurring phenomenon, most of the system-specific characterizations of the process have been reported only since 1990 [see the reviews of Bloesch (1995) and Evans (1994)]. There is a continuing need to document and characterize sediment resuspension, and to integrate its significance (Bloesch 1995) with other lentic processes and related study methods. Here we document and characterize sediment resuspension in Cannonsville Reservoir, NY. This study of the phenomenon is particularly noteworthy because of the conspicuous signatures manifested in widely used limnological measures and process analyses in this system, and the apparent interplay with drawdown (i.e., reservoir operation) of the reservoir's surface. Interferences with widely adopted paradigms are identified, and the interplay with hydrodynamic processes and related management issues is discussed.

Methods

System

Cannonsville Reservoir, NY (latitude 42 02'46", longitude 75 22'24", at dam) is a eutrophic water supply and flow augmentation reservoir for New York City (NYC; ~ 190 km away). It is the newest and third largest (of 19) of NYC's reservoirs. The principal axis of the reservoir corresponds to the riverbed of the West Branch of the Delaware River (WBDR). Water exits the reservoir by three routes: "spill" over the dam, release from deep layers at the dam to meet downstream flow requirements, and water supply withdrawals from one of three intakes (10, 20, and 37 m below the spillway elevation) from a mid-reservoir location (Fig. 1). All these flows are measured continuously by the NYC Department of Environmental Protection (NYCDEP). The reservoir has experienced substantial drawdown in many years of its operation; minimum water surface elevation (WSE) has usually occurred in late summer or early fall (Owens et al. 1998). For example, at its maximum drawdown in October 1995 (~ 20 m below crest), the reservoir's volume was reduced to about 23% of its crest capacity.

Detailed descriptions of the reservoir's morphometry, hydrology, operation (Owens et al. 1998), limnology (Effler and Bader 1998), and

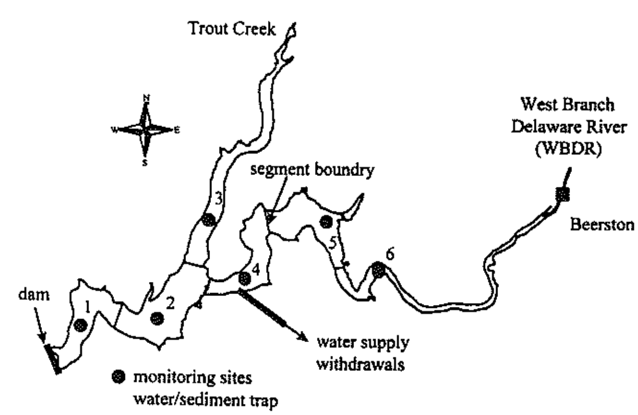

Figure 1.–Cannonsville Reservoir map, with watercolumn and sediment trap sampling locations for 1995, longitudinal segmentation for TSS watercolumn content and deposition calculations, and locations of water supply intakes, dam, and Beerston, NY.

watershed (Longabucco and Rafferty 1998) have been described elsewhere in this issue of the journal. Gradients in various water quality parameters, including concentrations and deposition rates of particulate constituents, prevail from the upstream boundary (Beerston, Fig. 1) of the reservoir (e.g., highest concentrations and deposition rates) to the dam (Effler and Bader 1998, Effler and Brooks 1998). The entire reservoir can be described as eutrophic (Effler and Bader 1998). However, the concentrations of volatile solids in the surficial sediments of the reservoir are relatively low, ranging from 5 to 9% of dry weight along the main axis of the reservoir (Erickson and Auer 1998). Autochthonous production of inorganic particles (other than diatoms) is expected to be minor in this dilute (Effler and Bader 1998) system.

Characterization and Analysis of Resuspension

Bloesch (1994, 1995) has reviewed methods to identify and characterize the occurrence of resuspension. Several of these approaches have been adopted here. Transmissometers, which provide a measure of the beam attenuation coefficient ($\underline{c}$), are widely used to assess the dynamics and spatial distributions of light scattering particles (Kirk 1994). Transmissiometry measurements have often been the primary basis of identifying the existence of a nepheloid layer above the sediment-water interface (e.g., Halfman and Johnson 1989, Pierson and Weyhenmeyer 1994, Sandilands and Mudroch 1983) and the occurrence of resuspension events (e.g., Gloor et al. 1994). Transmissometer profiles were collected weekly, from April through mid-October of 1995, in Cannonsville Reservoir at the six routine water quality monitoring sites (Fig. 1, also see Effler and Bader 1998). The beam transmissometer (Chelsea Instrument) was powered by a Seabird Sealogger Profiler (Model SBE 25); it has a path length of 25 cm and a nearly monochromatic light source (wavelength of 660 nm; $\underline{c}_{660}$). Readings were recorded at a rate of 8 per second, with an instrument descent rate of about 1.2 m · s^{-1}. Usually the resulting profile was the average of two "drops" of the instrument.

Suspended solids (TSS) concentrations were determined (APHA 1992) on samples from all six monitoring sites (depths of 0, 3, and 18 m at sites 1, 4, and 5; 0 and 3 m and near bottom at site 6; 0 and 18 m at site 5; and 0 m and near bottom at site 3) weekly over the reservoir monitoring period of 1995. Site 4 was also sampled proximate to the bottom as the reservoir was drawn down. Suspended solids concentrations were monitored in WBDR at Beerston over the period of reservoir monitoring as part of a long-term (and year-round) runoff event oriented program to support accurate estimates of loading for various constituents from this tributary (see Longabucco and Rafferty 1998).

Mass balance (input-export) calculations for TSS were made for the April-October interval of 1995 and compared to the magnitudes of downward flux [from Effler and Brooks (1998) and as presented subsequently here for September and October], the watercolumn pool of TSS, and variations in the watercolumn pool, to identify the operation of the resuspension process (e.g., Dillon et al. 1990). Hydrologic budget data were those available from NYCDEP and analyzed by Owens et al. (1998). External TSS loading estimates for WBDR were those developed by Longabucco and Rafferty (1998) for the 1995 study period, as well as for the October 1991-1995 interval. Other tributaries were ignored because WBDR represents ~ 80% of the total inflow (Owens et al. 1998), and concentrations are generally higher in this tributary (unpubl. data, NYCDEP). Export was calculated by multiplying the outflow(s) times the TSS concentration(s) from the most proximate monitoring site/depth. Calculations of downward flux and reservoir content accommodated the prevailing longitudinal gradients (see segmentation adopted in Fig. 1), the observed dynamics in deposition (Effler and Brooks 1998, and subsequently in this manuscript), and variations in hypsography associated with drawdown (Owens et al. 1998). The longitudinal segmentation (Fig. 1) corresponds approximately to mid-points between the monitoring sites.

A subset (n = 19) of the samples collected for TSS measurements were analyzed by scanning electron microscopy equipped with automated image analysis and x-ray energy spectroscopy. This individual particle analysis (IPA) technique provided both physical (size, shape, count) and chemical (elemental) characterizations of particles > 0.5 µm in diameter. The surficial sediment samples analyzed (n = 2) were collected from site 4 (Erickson and Auer 1998). Results from IPA have been found to be particularly valuable in evaluating the origins of particles (Effler and Johnson 1987, Effler et al. 1992, Johnson et al. 1991, Yin and Johnson 1984) and supporting the partitioning of turbidity and light scattering according to contributing particle types (Effler and Perkins 1996, Effler et al. 1998b). An additional eight samples were morphometrically characterized (scanning electron microscopy with automated image analysis, only). Detailed descriptions of sample preparation and analysis procedures have been presented by Yin and Johnson (1984) and Johnson et al. (1991). Information for 27 observation variables was obtained that includes relative x-ray emission intensity for 25 elements (Na, and higher atomic number), gross x-ray count rate, and projected feature area. These variables have been used to establish classification schemes to represent particle types according to chemistry. The classification schemes have ranged from rather detailed (e.g., 19 classes; Effler et al. 1992, Yin and Johnson 1984) to more broad, or generic classifications (e.g., 6 classes; Johnson et al. 1991). A simple scheme of 6 generic particle types (based on 24 specific classes) has been adopted for this analysis: organic, calcium-rich, clays, iron-rich, silica, and other (Table 1). IPA results are presented in terms of particle class concentrations, percent composition of the particle classes, and the particle cross-sectional area per unit volumn (PAV; e.g., Johnson et al. 1991) associated with the different classes. The PAV statistic has been found to be valuable in evaluating the implications for light scattering and turbidity (Effler and Perkins 1996, Owens 1974).

The sediment trap program conducted for the reservoir during the study period of 1995, including trap design, deployment, sample handling and analyses, and calculations, has been described previously (Effler and Brooks 1998). Here we report additional findings from that program that bear directly on the resuspension issue, including downward fluxes of volatile (and non-volatile, as the residual) suspended solids, downward fluxes of TSS measured at a deeper [~ 3 m above the sediment-water interface, versus the "below the thermocline" values reported by Effler and Brooks (1998)] position, and fluxes measured during the fall mixing period [from early September (Effler and Bader 1998)]. Selected aspects of the findings of Effler and Brooks (1998) concerning deposition are also reviewed here within the context of the resuspension phenomenon.

Results and Discussion

A Benthic Nepheloid Layer in Cannonsville Reservoir

Benthic nepheloid layers (BNLs) are turbid strata that overlie the sediment-water interfaces of aquatic systems, characterized by relatively high concentrations of suspended material, and typically identified by increased light scattering relative to overlying layers (e.g., Halfman and Johnson 1989, Hawley and Murphy 1995, Link 1994, Sandilands and Mudroch 1983). Transmissometry profiles at site 4 (Fig. 2) reflect substantial vertical and seasonal structure in the distribution of particles in the watercolumn of Cannonsville Reservoir during the study period of 1995. Values of $\underline{c}_{660}$ are regulated by light scattering (i.e., particles) in this system (Effler et al. 1998b). Values of $\underline{c}_{660}$ were generally higher in the upper waters and decreased in underlying mid-depth layers. Clear increases in the lowermost layers with the approach to sediment water interface, delineating the presence of a BNL, started to emerge by mid-to-late June (Fig. 2m), became conspicuous by mid-July (e.g., Fig. 2o), and persisted to the end of the study (Fig. 2z).

The presence of a BNL is widely accepted as a manifestation of the resuspension process (Bloesch 1994, 1995, Evans 1994). The specific origins and processes responsible for the formation and maintenance of BNLs are the subject of debate and substantial speculation (e.g., Bloesch 1995, Evans 1994,

Table 1.–Net X-ray chemical classification for generic particle types.

Type	Net x-ray criteria	# specific sub-classes	comments
organic	Net x-rays < 600 for 5 sec. live time	(2)	organic detritus
calcium	Ca x-rays > 50%	(6)	calcite, dolomite, and Ca rich aggregates with Si or Clay
clays	Al x-rays > 3%, Si x-rays > 47%	(6)	general aluminosilicate materials
iron	Fe x-rays > 50%	(6)	general high Fe, subclasses with Mn, Si, and S
silica	Al < 3%, Si x-rays > 60%	(2)	quartz and amorphous silica
other	Net x-rays > 600	(3)	anything else, subclasses for Ti and Cl/P rich, plus miscellaneous

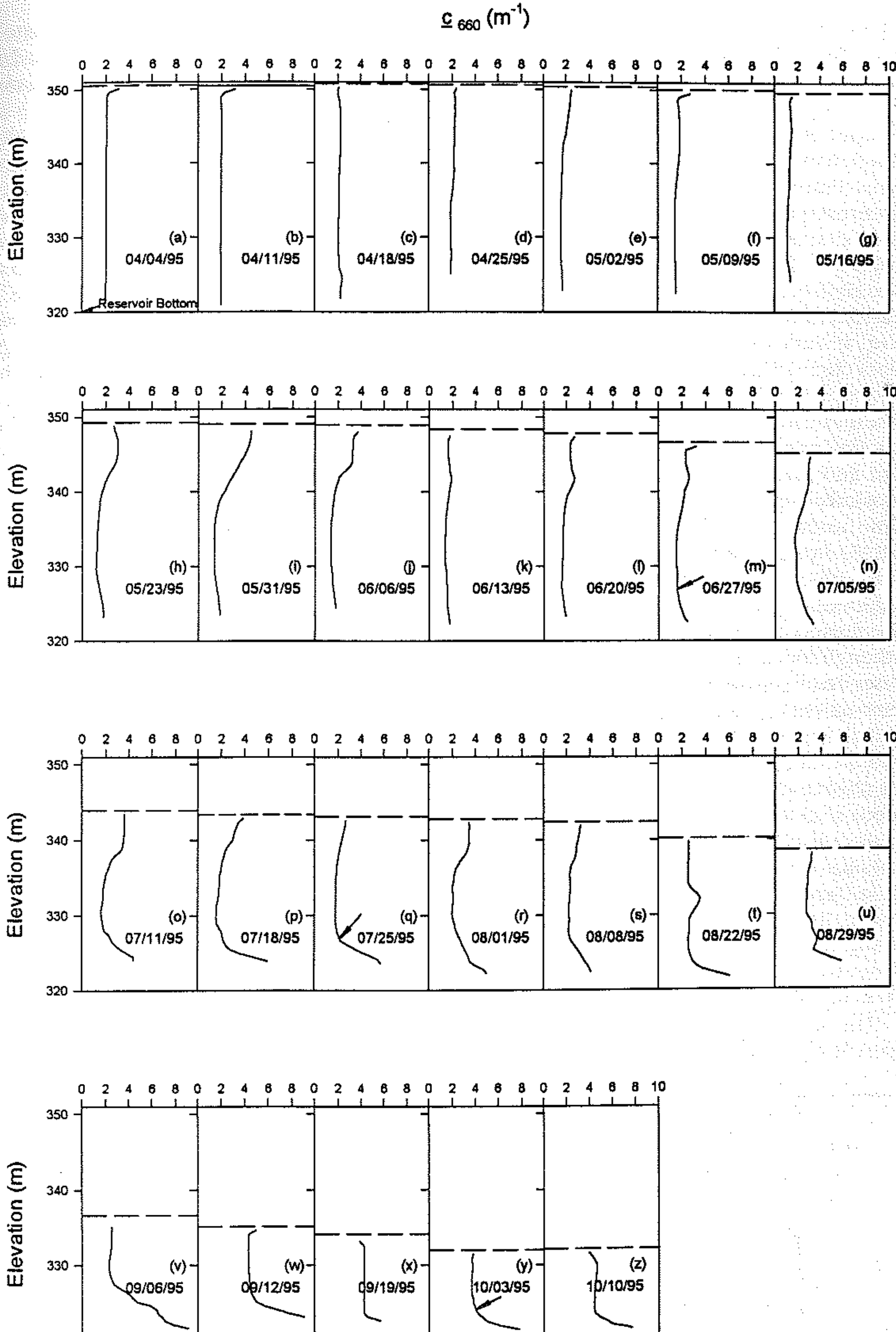

Figure 2.–Profiles of the beam attenuation coefficient (c_{660}) from transmissometry at site 4 on Cannonsville Reservoir, over the April-October interval of 1995: a) April 4, b) April 11, c) April 18, d) April 25, e) May 2, f) May 9, g) May16, h) May 23, i) May 31, j) June 6, k) June 13, l) June 20, m) June 27, n) July 5, o) July 11, p) July 18, q) July 25, r) August 1, s) August 8, t) August 22, u) August 29, v) Setember 6, w) September 12, x) September 19, y) October3, and z) October 10. Arrows on selected (4) profiles depict the upper boundary of the nepheloid layer.

Hawley and Murthy 1995) and are probably highly system-specific. Bloesch (1995) speculated that the particles of BNLs of most stratified systems (where they occur) do not originate from nearby hypolimnetic sediment resuspension because the deep currents are not strong enough to create the necessary shear stress. He indicated it is more likely these particles are derived from nearshore resuspension and subsequent transport via a "sediment focusing" process. Based on near-bottom current monitoring (14 d duration) in southwestern Lake Ontario, Hawely and Murthy (1995) concluded the shear associated with bottom currents was inadequate to account for the BNL of that system. However, Gloor et al. (1994) gave compelling evidence that seiche activity within the hypolimnion was responsible for the formation of a BNL in Lake Alpnach (Switzerland). Halfman and Johnson (1989) attributed the formation and maintenance of the BNL in the western arm of Lake Superior to sediment introduced by density flow (underflows) and local resuspension. Mudroch and Mudroch (1992) suggested some of the particles of the BNL of Lake Ontario had recently settled from the epilimnion. The origins of the BNL in Cannonsville Reservoir in mid-summer remain unresolved, though contributions from more than one of the processes described above are likely.

The higher values of c_{660} in the upper layers (relative to mid-depths) were in part associated with phytoplankton, but inorganic particles made increasing contributions starting in late June (Effler et al. 1998b, and subsequent sections of this manuscript) as the WSE dropped rapidly (Fig. 2). A mid-depth (thermocline) maximum was observed on a single occasion in late August (Fig. 2t). Increases in particle concentrations in the BNL from mid-June through late July, and again in August and September, are suggested by the increases in c_{660}. The value of c_{660} increased within the BNL as the sediment-water interface was approached (Fig. 2). Values of $c_{660} > 15$ m^{-1} were measured on several occasions (but not resolved in

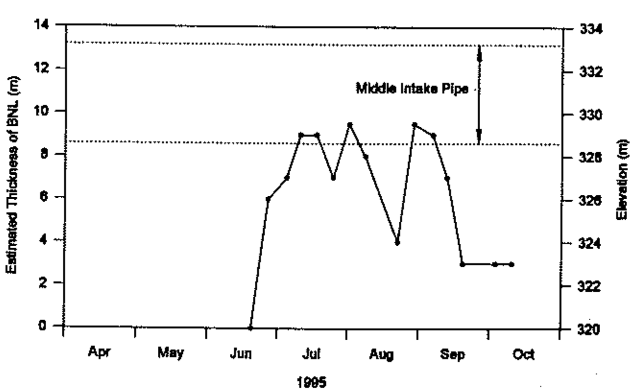

Figure 3.–Thickness of the nepheloid layer at site 4 in Cannonsville Reservoir over the April-October interval of 1995. Vertical position of the proximate middle intake for water supply withdrawals shown.

Fig. 2). Yet higher values probably would have been encountered, if the sediment-water interface had been more closely approached with the transmissometer (Fig. 2). The coincidence of the deepening of the upper mixed layer (Gelda et al. 1998, Owens 1998) and the reduction in the vertical dimensions of the BNL (Fig. 2) during the fall mixing period (e.g., mid-September) strongly suggest the attendant increases in c_{660} throughout the upper layers were, at least in part, a result of entrainment of portions of the BNL.

The upper boundary of the BNL at site 4 was determined by visual inspection, e.g., usually it was only slightly above the maximum gradient in c_{660} (see Fig. 2). The onset of establishment of the layer in 1995 is open to some debate. The BNL thickness at site 4 increased from about 6 to 9 m from mid-June to early July and varied through early September (Fig. 3). Some of the apparent variations in the thickness of the BNL may reflect the influence of seiche activity (e.g., oscillations). A major decrease was observed in mid-August, and again in early to mid-September (Fig. 3). The later decrease reflects the deepening of the upper mixed layer with the approach to the onset of complete fall turnover. The BNL at site 4 may have implications for the quality of the water supply (intake ~ 0.3 km from site 4) as this layer of high particle concentrations (e.g., high turbidity) extended above the lowermost intake and entered into the depth range of the middle intake (Fig. 3) during the study period of 1995. The lowermost intake (centerline elevation of 315.7 m) is almost never used for the water supply because of high turbidity. This may be associated with the BNL. Local scour from recent deposits in the vicinity of the intake is an alternate explanation, or perhaps a contributing factor. The discontinued use of Cannonsville Reservoir for water supply in late August of 1995 was partially in response to elevated turbidities in the downstream aqueduct, perhaps associated with inputs from the BNL.

Comparison of c_{660} profiles from the different monitoring sites establishes that there was substantial spatial structure in the occurrence of the BNL in the reservoir in 1995 (e.g., Fig. 4). No BNL was encountered at site 1 (the deepest location, Fig. 1) or site 5 on July 11, despite the well established signature of such a layer at sites 3 (Trout Creek arm, Fig. 1) and 4 (Fig. 4a). Site 2 had a distinct maximum about 2 m above the bottom (Fig. 4); e.g., perhaps as an outcome of exchange between areas with (site 4) and without (site 1) a BNL (see Fig. 1). In sharp contrast, a well-defined BNL was present at site 2, as well as sites 3 and 4, on September 12 (Fig. 4b). Spatial heterogeneity in the occurrence and dimensions of BNLs has been described for larger lakes (e.g., Link 1994, Sandilands and Mudroch 1983). The phenomenon has usually been associated with the deeper portions of basins. Contrary to the observations for Cannonsville Reservoir (e.g., Fig. 4), Sandilands and Mudroch (1983) observed a significant positive correlation between water depth and the thickness of the BNL in Lake Ontario. Factors contributing to the spatial heterogeneity observed in this reservoir are open to speculation. Local sources of resuspension, combined with bathymetric irregularities (not presently resolved from the available bathymetry), is one possibility. The comparative absence of a BNL at site 1 (a thin BNL was observed from mid-September to mid-October) may reflect an outcome of bottom releases at the dam (average of ~ 20 $m^3 \cdot s^{-1}$ over the July-August interval of 1995); e.g., particles that would contribute to a BNL at this location may have already been exported downstream. The dynamics observed at site 2 (e.g., Fig. 4a and b), including the vertical structure of July 11, could be consistent with such a scenario.

The persistence of a relatively thin BNL (~ 3 m) through mid-October (Figs. 2w-z, 4b) is, at least in part, a result of the entry of a dense underflow from WBDR (Owens 1998). The origin of the density difference at the upstream boundary of the reservoir is the lower temperatures of the WBDR relative to the reservoir in the fall (Owens 1998). Lotic systems generally cool more rapidly than proximate lentic systems in the fall in temperature regions, making inflows more dense. Elevated velocities, and greater propensity for resuspension, thereby exist at the reservoir bottom within the dimensions of the underflow, when this phenomenon prevails. Increases in the density of the underflow may occur from enrichment with sediment (Ford and Johnson 1983) from upstream portions of the reservoir, which would promote the extension of the turbid BNL (as an underflow) to the lower portions of the reservoir during this period (e.g., Fig. 4b).

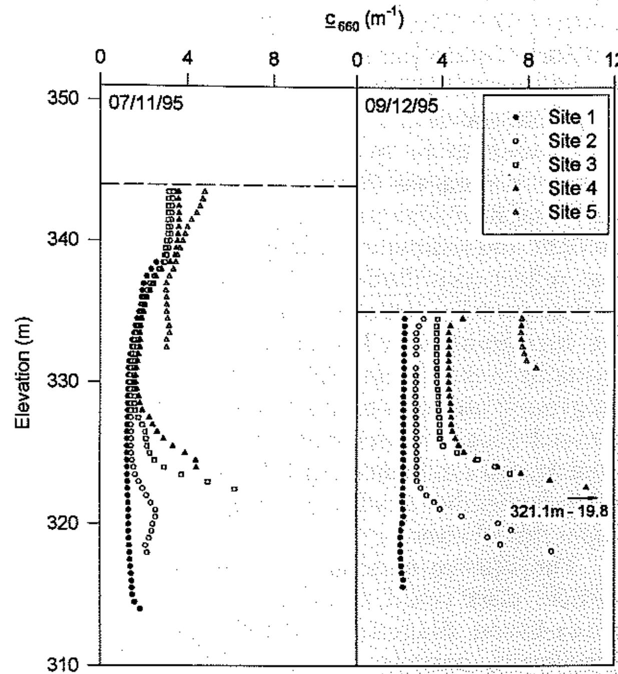

Figure 4.–Comparison of profiles of the beam attenuation coefficient (c_{660}) from transmissometry at five sites on Cannonsville Reservoir: a) July 11, 1995, and b) September 12, 1995.

IPA Evidence for Resuspension

Comparison of IPA characterizations of the chemistry of particles from the reservoir's water column, sediments, and WBDR (Table 2) establishes the rather uniform composition of major components of the inorganic particle populations within the system and the regulatory role of watershed inputs. The contribution of the summation of the clay and silica particle

Table 2.–Comparison of chemical composition of particles from the Cannonsville Reservoir system in 1995, according to IPA particle type (% of total particles).

Particle Type	WBDR+ n= 4	epilimnion (n = 5) May 23 - June 13	Water Column epilimnion (n = 5) July 26 - Sept. 12	hypolimnion (n = 5) July 26 - Sept. 12	Sediments (n = 2)
organic	13.9	15.6	12.4	9.0	6.4
calcium	1.2	1.0	4.2	0.2	0.4
clays	27.9	28.5	33.0	35.1	32.9
iron	8.0	5.6	5.9	16.0	8.7
silica	39.3	44.3	36.0	32.5	42.2
other	9.8	4.9	8.5	7.6	4.5

+ at Beerston (Fig. 1)

types for all these locations fell within the rather narrow range of 67 to 75% (see Table 2). Autochthonous production of silica particles occurs in lakes and reservoirs associated with the formation of diatom frustules (e.g., Johnson et al. 1991). Most of the silica particles were found to be quartz, though diatom frustules made contributions (Effler et al. 1998b). The higher percentages of silica particles in the early summer epilimnetic and sediment particle populations (Table 2) may reflect contributions from diatoms. The higher average contribution of iron-rich particles reported for the hypolimnion in late summer relative to other locations in the system (Table 2) is a manifestation of progressive increases of this class within the BNL. The iron-rich class increased from 8 to 36% of the particles from August 1 to September 6, but decreased to about 8% by September 12 with the abrupt deepening of the upper mixed layer.

The relative enrichment of the BNL with this particle class could result from the operation of redox-based diagenetic sedimentary processes. Specifically, particles residing within the surficial sediments of the BNL are expected to become enriched with iron from the precipitation/adsorption of Fe^{3+}, as upward diffusing Fe^{2+} (pore waters) encounters an oxidizing environment (e.g., Mortimer 1941, 1942). Accordingly, the progressive enrichment of the BNL with iron-rich particles could be interpreted to support the input of local surficial sediments. However, there is conflicting evidence for such an interpretation. Anoxia prevailed in the lowermost layers of the reservoir at site 4 during the interval of enrichment, yet no Fe^{2+} was detected in these layers (Effler and Bader 1998). This is consistent with thermodynamic considerations (Froelich et al. 1979), as the hypolimnetic nitrate pool was only partially depleted during the anoxic interval of 1995 (Effler and Bader 1998). The lower contribution of iron-rich particles reported for the lake's sediments (Table 2) is also incongruent with the above hypotheses, though these samples may not have been representative of the particle population at the sediment-water interface (e.g., false low concentrations of iron-rich particles) because of limitations in the collection methods.

Effler and Bader (1998) reported systematic reductions in the clarity of the epilimnion during the late summer in 1995, as the reservoir was drawn down (Fig. 5a), in the absence of coupled systematic increases in phytoplankton biomass. They hypothesized the reduced clarity was attributable to systematic increases in non-phytoplankton particles. Effler et al. (1998b) reported progressive increases in the turbidity of the epilimnion over the same period (Fig. 5b). The increase in particle concentrations in the upper waters over the same period (Fig. 5c, from scanning electron microscopy with automated image analysis) is generally consistent with the observed increase in turbidity (Fig. 5b) and decrease in clarity (Effler and Bader 1998). Chemical characterization (energy X-ray spectroscopy) of the particle population for a subset of the samples analyzed with the scanning electron microscope (Fig. 5c) indeed establishes a major increase in the PAV of non-phytoplankton particles occurred during late summer in the upper waters of the reservoir

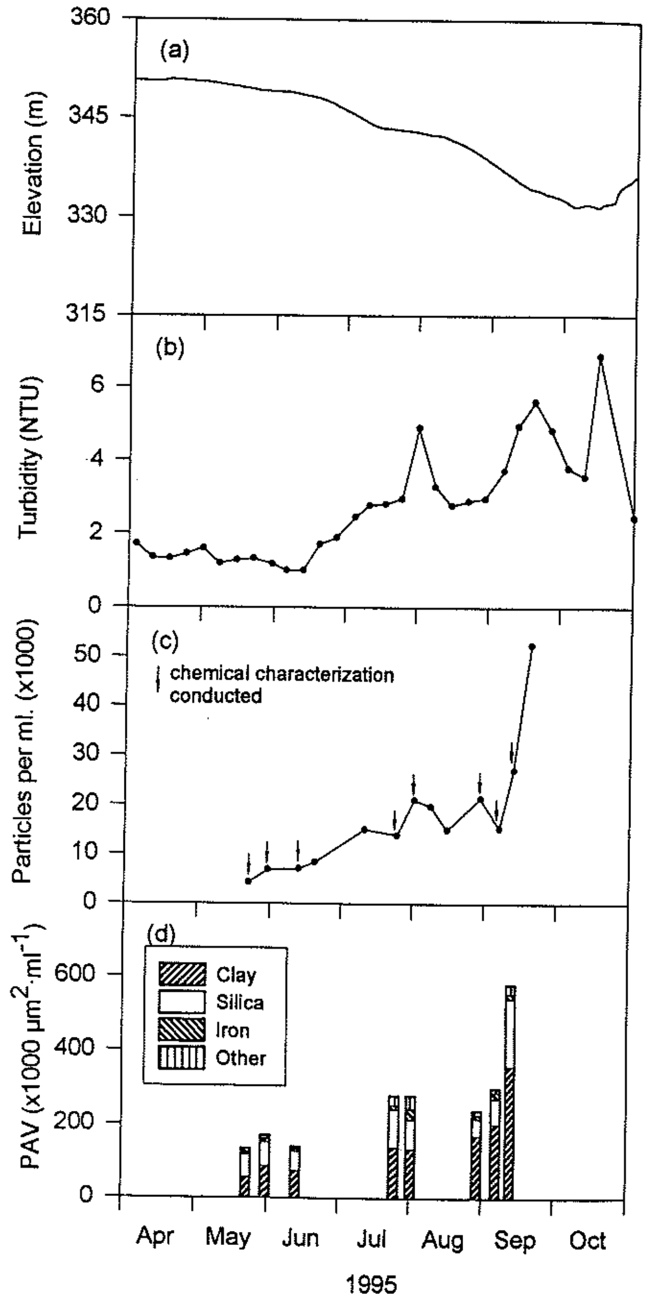

Figure 5.–Time-series for Cannonsville Reservoir for the April-October interval of 1995: a) WSE (Effler and Bader 1998), b) turbidity in the upper waters (from Effler et al. 1998b), c) particle concentrations in the upper waters, d) PAV in the upper waters, resolved according to generic particle type.

(Fig. 5d), linking this to the observed increase in turbidity (Fig. 5b; see Effler et al. 1998b). The contributions of the inorganic particle population to light scattering and turbidity in the reservoir in 1995, including the influence of a shift to smaller particle size distribution, receive more rigorous quantitative treatment within the context of related optical theory, elsewhere in this issue (Effler et al. 1998b). The greatest increases in non-phytoplankton particle PAV occurred in the clay particle class. These increases in inorganic particle PAV and turbidity were largely a result of resuspension as external TSS loading was low during this period (Longabucco and Rafferty 1998, and subsequently in this manuscript).

The increase in non-phytoplankton turbidity coincided with, and almost certainly was coupled to, the drawdown of the reservoir (Fig. 5a). The shift of bottom sediments toward smaller particle sizes with increasing water depth is well known (e.g., Sly et al. 1982, Thomas et al. 1972). Further, portions of the lake bottom that were previously below the wave base and not subject to the associated large shear stress can accumulate particles that will be subject to resuspension as the WSE drops. Thus it is reasonable to expect a reservoir shoreline to become progressively more susceptible to resuspension, and the imparted turbidity to be more persistent (e.g., particles with reduced settling velocity), as drawdown proceeds. We hypothesize that the effect of resuspension on the turbidity of the upper waters would be reduced for years in which less drawdown occurs.

Sediment Trap Studies

Approximately 70% of the dry weight (TSS) deposition from the epilimnion of Cannonsville Reservoir at site 4 over the April-August interval of 1995 was non-volatile (inorganic) particles (Fig. 6). Further, this fraction largely regulated the dynamics of TSS deposition (Fig. 6a-c). This is generally consistent with the important role the inorganic component plays in the watercolumn particle population. Based on NYCDEP monitoring data (unpublished) for the 1989-1995 period, the inorganic component of epilimnetic suspended solids averaged (n = 48) 42% of TSS at this site. The greater contribution of this fraction in the trap collections of the summer of 1995 (Fig. 6a-c) is consistent with the greater densities, and therefore settling velocities, of inorganic particles compared to organic particles (Table 3, also see Effler and Brooks 1998). Results from IPA (Table 2) establish the inorganic deposition was almost entirely material that was ultimately derived from the reservoir's watershed.

Resuspension was further manifested in two ways in the TSS sediment trap results (Fig. 6). First, downward fluxes were systematically higher during the fall mixing period (September and October, Fig. 6a). This is a widely observed manifestation of resuspension, reflecting redeposition of resuspended sediment (Bloesch 1995). Note that these higher fluxes were preferentially associated with the inorganic fraction in Cannonsville Reservoir; more than 80% of the

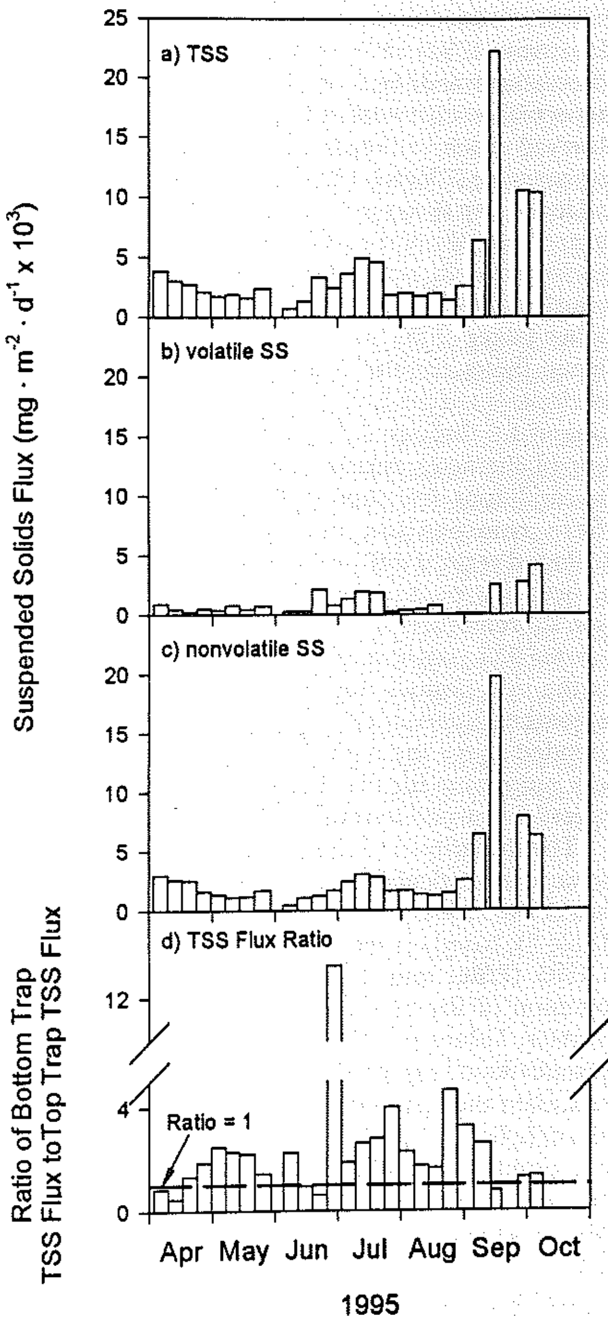

Figure 6.–Time series of downward fluxes from the epiliminion of Cannonsville Reservoir, at site 4: a) TSS (April-August data from Effler and Brooks 1998), b) volatile SS, c) non-volatile SS, and d) time series of the ratio of bottom (3 m above sediments) to top (as presented in a)) TSS fluxes at site 4.

downward flux of TSS was inorganic for the September and October trap collections (Fig. 6a-c). Much of the increase may reflect deposition of particles from the BNL, entrained during fall mixing, rather than redeposition of bottom sediment recently resuspended from deep water areas. Secondly, the higher fluxes observed in the near bottom trap compared to the upper trap (ratios > 1, Fig. 6d) during summer stratification are also indicative of redeposition of resuspended sediment (Bloesch 1994, 1995, Evans and Hakanson 1992). While not widely documented, observations made by Bloesch and coworkers lead him to speculate such vertical differences in fluxes would be observed widely in deep lakes, if assessed, as a result of resuspension (Bloesch 1995). Comparison of the upper and lower trap fluxes in Cannonsville Reservoir should be resolved temporally according to the occurrence of the distinct BNL, as this demarcates differences in the contributions of the various particle sources for the higher fluxes of the near-bottom trap. The generally higher fluxes for the near-bottom trap before the development of the BNL (Figs. 4 and 6d; average ratio value of 1.6 through early June) were comparable in general character, relative magnitude, and setting to the conditions described by Bloesch (1995) for lakes where resuspension occurred. Bloesch (1995) attributed vertical differences in flux of this character to focusing-type transport of sediment resuspended from shoreline areas of the epilimnion. Redeposition from the BNL contributed to the higher fluxes measured for the near-bottom trap over the mid-June to early September interval (Fig. 6d), as this turbid layer extended above the deployment depth (Fig. 4). The peak ratio value for the fluxes in late June (Fig. 6d) suggests a resuspension event that remains unexplained.

The disparity in settling velocities (SVs) reported for various particulate constituents from the epilimnion of the lacustrine zone of Cannonsville Reservoir (Table 3), based on sediment trap studies performed in 1995 (Effler and Brooks 1998), also reflects the operation of the resuspension phenomenon in the reservoir. Values of SV for constituents common to phytoplankton [e.g., particulate organic carbon (POC), particulate nitrogen, particulate phosphorus (PP), and chlorophyll (C_T)] generally match each other where phytoplankton dominate the particle assemblage containing these materials (e.g., Baines and Pace 1994, Callieri et al. 1991). The distinctly higher SVs determined for POC (and volatile SS) and PP compared to C_T in Cannonsville Reservoir (Table 3) depict contributions of these constituents from non-phytoplankton particles that settle more rapidly than phytoplankton (Effler and Brooks 1998). Results of the mass balance analysis for TSS (subsequently), together with the chemical characterization of particles from the reservoir's water column (Table 2), give compelling evidence that the non-phytoplankton particles are largely resuspended sediment, ultimately derived from the watershed. The particularly high SV for PP (Table 3) establishes much of the depositing phosphorus is associated with inorganic particles (e.g., clays, see Table 2). The stoichiometry of depositing particles was substantially shifted from that of phytoplankton in 1995 due to the contribution of non-phytoplankton particles (Effler and Brooks 1998). Failure to recognize the operation of the resuspension phenomenon and its effect on particle stoichiometry could result in misleading conclusions concerning the nutrient status of the phytoplankton of this reservoir, as well as other affected systems (e.g., Effler and Brooks 1998, Hecky et al. 1993).

TSS Budget

Comparison of the results of mass balance calculations for TSS (Fig. 7a and b) to the downward flux (Fig. 7c) and watercolumn content (Fig. 7d and c) of TSS clearly establishes the operation of the resuspension phenomenon in Cannonsville Reservoir during the study period of 1995 (also see Table 4). The external load to the reservoir over the April-October interval was low relative to the load received over the October 1991-1995 period (Fig. 7a) because of the low flows that prevailed in WBDR (also see Longabucco and Rafferty 1998). More TSS was exported (Fig. 7b) than received. The negative retention (see inset of Fig. 7b, Table 4) is consistent with the operation of sediment resuspension during that interval. Retention is more meaningful within the context of an annual budget (e.g., Dillon et al. 1990). Clearly strong seasonal

Table 3.–Summer average settling velocities of particulate constituents from the epilimnion of the lacustrine zone of Cannonsville Reservoir [modified from Effler and Brooks (1998)].

Constituent	Settling Velocity ($m \cdot d^{-1}$)
TSS	0.73
non-volatile SS	1.4
volatile SS	0.4
POC*	0.32
PP*	0.88
C_T*	0.17

* C, PP, C_T - particulate organic carbon, particulate phosphorus, and total chlorophyll, respectively.

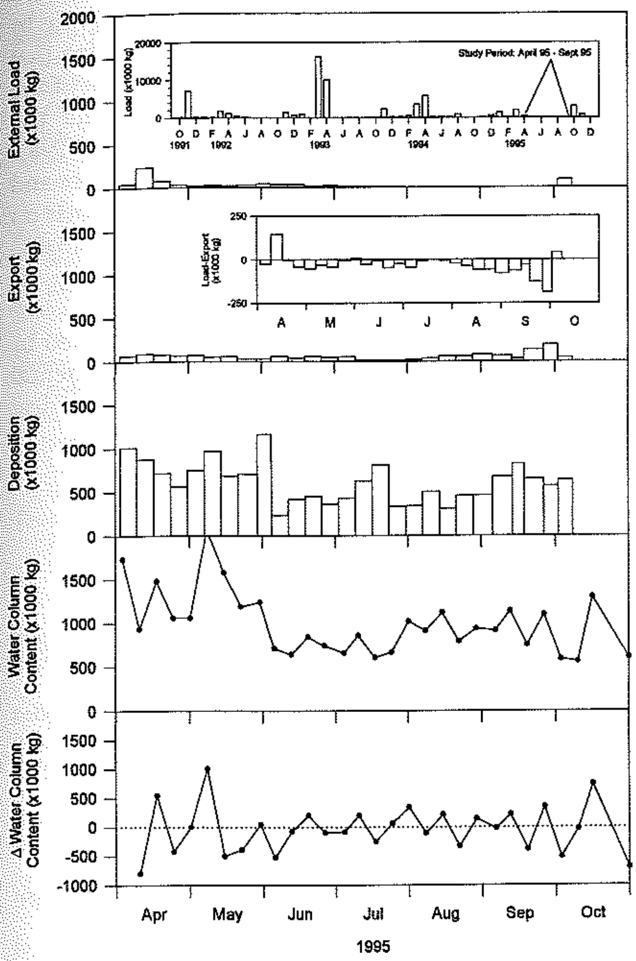

Figure 7.–Estimates for TSS for Cannonsville Reservoir for the April-October interval of 1995: a) external load from WBDR (inset of monthly loads from October 1991 through 1995), b) export (inset of external load, from a), minus export), c) deposition, d) watercolumn content, and e) changes in watercolumn content between monitoring dates.

and interannual variations in external loading have prevailed (Fig. 7a). The annual retention estimate (Table 4) should be considered a first approximation. It is based on the total load for the period of event-based monitoring of WBDR (October 1991-1995; Longabucco and Rafferty 1998) and the assumption that the export rate estimated for the monitored interval of 1995 is representative on an annual basis. According to this calculation (Table 4), the average retention of the external TSS load to the reservoir is about 80%. The failure to consider contributions to export from autochthonous (e.g., organic) production tends to be compensated for by the omission of minor tributary inputs in the loading calculation.

The downward flux of TSS was more than 20 times greater than the external load over the April - early October interval of 1995 (Fig. 7c), and the annual estimate of flux exceeded the longer-term annual load by more than a factor of two (Table 4). The estimate of annual deposition (70 to 80% inorganic, Fig. 6a-c) was nearly three times greater than the estimated TSS retention, clearly delineating the operation of the sediment resuspension process (Bloesch 1995, Dillon et al. 1990). Modest changes in the relative magnitudes of the fluxes for long-term (average) conditions could occur if deposition rates for "full" reservoir years were found to be systematically different from those reported for 1995 (Effler and Brooks 1998). According to this budget analysis, approximately 65% of the TSS deposited is resuspended (and subsequently re-deposited; Table 4). Sediment resuspension was also manifested in the large magnitude of the watercolumn pool of TSS (Fig. 7d) and short-term variations in the pool (Fig. 7e), that prevailed during the study period.

Table 4.–Features of TSS budget calculations for Cannonsville Reservoir.

Component	Value	Description
1. external load(s)		WBDR
a. April 3 - October 9, 1995	7.6×10^5 kg	
b. October 1991 - December 1995	6.4×10^7 kg	
c. average annual rate	1.5×10^7 $kg \cdot y^{-1}$	calculated from 1b.
2. export		
a. April 3 - October 9, 1995	1.6×10^6 kg	
b. annual rate for 1995	3.1×10^6 $kg \cdot y^{-1}$	estimated from 2a.
3. retention		external load minus export
a. April 3 - October 9, 1995	-8.4×10^5	1a. minus 2a.
b. retention rate (annual)	1.2×10^7 $kg \cdot y^{-1}$	1c. minus 2b.
4. deposition		from sediment traps
a. April 3 - October 9. 1995	1.7 x 10 kg	
b. assumed annual	3.4×10^7 $kg \cdot y^{-1}$	two x 4a.
5. resuspension	2.2×10^7 $kg \cdot y^{-1}$	4b. minus 3b.

The water column contained much more TSS over the April-October interval of 1995 (Fig. 7d) than was received as external loading (Fig. 7a), and variations in the watercolumn pool (Fig. 7e) were large compared to the load. These differences cannot be explained by autochthonous production, as the inorganic fraction of the watercolumn content (~ 40% of the total) remained greater than could be explained by external loading during the study period.

Management Perspectives

The operation of the sediment resuspension process was identified and characterized in Cannonsville Reservoir for 1995, a major drawdown year, through a diverse array of methodologies, including transmissometry profiling, application of IPA techniques, analysis of sediment trap collections, and mass balance calculations. The phenomenon is of concern for managers of this water supply, and other water supplies where the process occurs, because it causes increases in watercolumn turbidity, an important feature of water quality. In this reservoir, the increased turbidity was observed as a BNL and also as increases in inorganic particle concentrations in the upper waters. We have hypothesized that the resuspension process is promoted, and related turbidity problems exacerbated, by greater drawdowns of the reservoir's surface. This implies there is a water quality cost for the operation of Cannonsville Reservoir for its intended use. The hypothesis should be tested through appropriate monitoring for a range of reservoir operating conditions (e.g., covering a wide range of annual runoff), and ultimately the development and testing of a mechanistic model capable of accurate simulation of resuspension fluxes in response to forcing conditions. The vertical dimensions and location of the BNL in 1995 indicate the potential for this turbid layer to directly impinge on the operation of the water supply intakes and the turbidity of withdrawn water.

There is evidence that particles resuspended into the upper waters of the reservoir confounded certain signatures commonly attributable to trophic state. For example, much of the turbidity (and loss of clarity; also see Effler and Bader 1998, Effler et al. 1998b) during the interval of major drawdown in the late summer of 1995 was associated with non-phytoplankton particles. These non-phytoplankton particles shifted the stoichiometry and settling velocities of settling particles from values associated with phytoplankton. Further, a substantial fraction of the total phosphorus concentration (TP) in the late summer of 1995 was almost certainly associated with resuspended inorganic particles rather than phytoplankton. The under-prediction of TP and particulate phosphorus by the eutrophication model for the reservoir for that period has been largely attributed to omission of the contri-bution of resuspended particles from the phosphorus budget of the model (Doerr et al. 1998). Managers need to be cognizant of the occurrence and form of such interferences so that related impacts on common measures of water quality can be differentiated from those of phytoplankton growth.

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