SEDIMENT RESUSPENSION AND DRAWDOWN IN A WATER SUPPLY RESERVOIR

Steven W. Effler and David A. Matthews

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.)

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
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 metalmic 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 $373 \times 10^6$ m$^3$, a surface area of $19.3 \times 10^6$ 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 2.66/y, with a range of 1.9 to 3.66/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.
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 metalimnion (g/m³). The value of PC was determined as the area of the trap opening (A; m²) according to the relationship

\[ \text{PC} = \frac{\text{W}}{(\text{A} \times t)} \]  

(1)

where PC is the particulate concentration in the epilimnion (g/m³). 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 DFₜsₜ, (2) the contribution of inorganic particles (FSS) to DFₜsₜ, and (3) the contribution of resuspended organic particles to overall organic particle deposition. The calculations are based on linear least squares regressions of DFₜsₜ versus DFₚₜ and DFₚₜ versus DFₜₚ (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 DFₜsₜ 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.

\[ r^2 = 0.95 \]
\[ \text{DF}_{\text{EPI}} = 0.976 \cdot \text{DF}_{\text{META}} - 0.416 \]
\[ n = 27 \]

![Figure 2. Evaluation of the Relationship Between \(\text{DF}_{\text{TSS}}\) Values From Paired Epilimnetic and Metalimnetic Deployments at Site 4L4 in 2002, With Summary of Results of Linear Least Squares Regression.](image)

### 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 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 \(\text{DF}_{\text{TSS}}\) and \(\text{DF}_{\text{FSS}}\) 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 \(\text{DF}_{\text{FSS}}\) explained equal to or greater than 99 percent of the variations in \(\text{DF}_{\text{TSS}}\) at each site in both years, according to linear least squares regression. Since \(\text{DF}_{\text{FSS}}\) 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, \(\Delta T\)) (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 \(\Delta T\)) 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 \(c_{660}\) 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 \(c_{660}\) profiles is invaluable in depicting the distribution of particles. The increase in \(c_{660}\) 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
accepted as a manifestation of the operation of resuspension processes (e.g., Halfman and Johnson, 1989; Piersen 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 \( c_{660} \) 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 \( c_{660} \) 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 3. Time Series of WSE, DF_{TSS}, DF_{FSS}, and \( \Delta T \) for Metalimnetic Deployments Along the Reservoir’s Primary Axis in 2001 and 2002: (a) WSE, 2001, (b) Site 6 DFs and \( \Delta T \), 2001, (c) Site 5.5 DFs, 2001, (d) Site 5 DFs and \( \Delta T \), 2001, (e) Site 4.5 DFs, 2001, (f) Site 4 DFs and \( \Delta T \), 2001, (g) Site 2.5 DFs and \( \Delta T \), 2001, (h) WSE, 2002, (i) Site 6 DFs and \( \Delta T \), 2002, (j) Site 5.5 DFs and \( \Delta T \), 2002, (k) Site 5 DFs and \( \Delta T \), 2002, (l) Site 4.5 and \( \Delta T \), 2002, (m) Site 4 DFs and \( \Delta T \), 2002, and (n) Site 2.5 DFs and \( \Delta T \), 2002.
that portion of the reservoir (Gelda et al., 1998), a net increase was estimated in the water column content of $c_{660}$ (treating it in a manner akin to concentration) from October 3 to October 17 of more than 20 percent. This suggests the increased $c_{660}$ 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.

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/m²/d. The highest y-intercept values were observed for Site 6 (0.63 and 0.84 g/m²/d, in 2001 and 2002, respectively). Values for all other sites were in a rather narrow range (0.28 to 0.47 g/m²/d), except Site 5.5 in 2002 (0.15 g/m²/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.

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 DFTSS 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 DFTSS 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
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 DFTSS 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\textsubscript{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>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Total Resuspension (percent)</th>
<th>Inorganic Resuspension (percent)</th>
<th>Organic Resuspension (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Median</td>
<td>Mean</td>
</tr>
<tr>
<td>6</td>
<td>2001</td>
<td>83 to 100</td>
<td>83</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>62 to 98</td>
<td>89</td>
<td>88</td>
</tr>
<tr>
<td>5.5</td>
<td>2001</td>
<td>78 to 100</td>
<td>89</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>87 to 100</td>
<td>97</td>
<td>96</td>
</tr>
<tr>
<td>5</td>
<td>2001</td>
<td>76 to 100</td>
<td>89</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>83 to 100</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>4.5</td>
<td>2001</td>
<td>69 to 100</td>
<td>85</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>71 to 100</td>
<td>90</td>
<td>89</td>
</tr>
<tr>
<td>4L4</td>
<td>2001</td>
<td>67 to 100</td>
<td>79</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>62 to 100</td>
<td>90</td>
<td>87</td>
</tr>
<tr>
<td>2.5</td>
<td>2001</td>
<td>54 to 100</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>43 to 100</td>
<td>91</td>
<td>85</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Time Segment</th>
<th>WSE (m) 2001</th>
<th>WSE (m) 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>May to July</td>
<td>349.4</td>
<td>347.2</td>
</tr>
<tr>
<td>August to September</td>
<td>341.1</td>
<td>339.2</td>
</tr>
<tr>
<td>October</td>
<td>330.9</td>
<td>336.9</td>
</tr>
</tbody>
</table>
Decreasing gradients in $DF_{\text{FSS}}$ 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 $DF_{\text{FSS}}$ 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 $DF_{\text{FSS}}$ for Sites 4.5, 4, and 2.5 were not significantly different for the two years (Table 3).

A clear gradient in $DF_{\text{FSS}}$ 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 $DF_{\text{FSS}}$ 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 $SV_{\text{FSS}}$ (Figures 7e and 7f). Of these two factors, $SV_{\text{FSS}}$ was by far the primary driver for the May to July interval in both years (compare Figures 7c and 7e). The gradient(s) in $SV_{\text{FSS}}$ indicates a mobilization of larger particles in upstream regions that settle more rapidly. The $SV_{\text{FSS}}$ 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 $SV_{\text{FSS}}$
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 SVFSS 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.

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 near-shore 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).

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 DFSS 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).

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 redeposited/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


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.


