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Turbidity and Particle Signatures Imparted by Runoff Events in Ashokan Reservoir, NY[1]

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ABSTRACT

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The occurrence, temporal and spatial patterns, and origins of turbidity events, and their linkage to runoff events, are documented for a water supply impoundment with two separated basins, Ashokan Reservoir, NY. The analysis is supported by a comprehensive 6-week study of the major inflow and the reservoir during the summer of 1996, that captured the effects of a single runoff event, and turbidity (T_n) measurements made in the reservoir and the water supply intakes for the entire year. Measurements supporting the short-term study include: temperature, specific conductance, beam attenuation coefficient, electronic particle counts, Secchi disc transparency, T_n, up- and downwelling cosine irradiance, chlorophyll, microscopy-based individual particle size and chemistry, and total suspended solids (TSS) on sediment trap collections. The external load of mostly quartz and clay particles delivered by the principal tributary, as an interflow, during the summer runoff event imparted distinct signatures in T_n and deposition within the epilimnion of the receiving basin; the other basin remained unaffected by comparison. The deposition rate of TSS and T_n increased in the receiving basin in response to the runoff-based loading; decreasing gradients in both parameters were observed within this basin downstream of the entry point of the tributary. More than 85% of T_n in the receiving basin during the 6-week study is attributed to inorganic tripton particles of terrigenous origins. Analysis of the longer-term data indicates elevated T_n values (maximum of 150 NTU) occur routinely in the receiving basin following runoff events, and that this effect extends to the other basin, including the water supply intake(s), during intervals other than summer stratification.

Key Words: reservoir, impoundment, turbidity, inorganic tripton, inorganic suspensoids, runoff event, optics, interflow, particle, deposition.

Turbidity (T_n), an optical property observed to be highly correlated with, and approximately numerically equal to, the scattering coefficient ($\underline{b}$) (e.g., DiToro 1978, Effler et al. 1991a, 1998b, Kirk 1981, Vant and Davies-Colley 1984, Weidemann and Bannister 1986), is a widely used measure of water quality. This analyte has particular importance for lakes and reservoirs used as water supplies, as T_n values must remain below a specified standard (< 5 NTU for water supplies in New York State). Turbidity is primarily a function of the number and size distribution of particles (e.g., Effler et al. 1998b), and secondarily, of particle composition (Kirk 1994). Thus, managers need to be aware of the type(s) of particles that regulate T_n in their water

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supplies, the origins of these particles, and the interplay of ambient environmental conditions and anthropogenic influences with the supply of particles to the water columns of these systems.

Turbidity is in general caused by a heterogeneous population of particles, which may include clay, silt, finely divided organic and inorganic material, phytoplankton, and other microscopic organisms (e.g., Effler and Johnson 1987). In general, this population of particles is a composite of sediments received in tributary (allochthonous) inputs, or resuspended lake deposits and particles produced within the water column (autochthonous inputs). Autochthonous formation of organic particles is usually observed to be dominated by phytoplankton production. Reduction of nutrient loading is the most widely used management approach (e.g., Cooke et al. 1993) to control turbidity in culturally eutrophic systems. The inanimate particles of the water column have been described as tripton (e.g., Wetzel 1983). Precipitation of carbonates (i.e., autochthonous input), a phenomenon known as "whiting," has been observed to be an important source of turbidity in the summer in a number of hardwater lakes (e.g., Effler 1987, Effler and Johnson 1987, Effler et al. 1991b). Tripton received in runoff has been observed to regulate T_n in a number of systems (e.g., Kirk 1985, 1994). For example, Effler et al. (1998b) demonstrated that inorganic tripton from the watershed of Cannonsville Reservoir [received mostly during runoff events (Longabucco and Rafferty 1998)], resuspended from the bottom (Effler et al. 1998a), was the primary component of T_n in the reservoir during the severe drawdown interval of 1995.

In this study we document an alternate case in which tripton supplied from a watershed regulates the dynamics of watercolumn T_n. This case, for Ashokan Reservoir, NY, contrasts that reported earlier for Cannonsville Reservoir, NY (Effler et al. 1998a, b), in that responses are demonstrated to be more temporally coupled (immediate) to runoff events. Further, we describe tributary forcing conditions; in-reservoir temporal and spatial patterns in particle composition, size, and concentration; T_n; and sediment deposition imparted from runoff events.

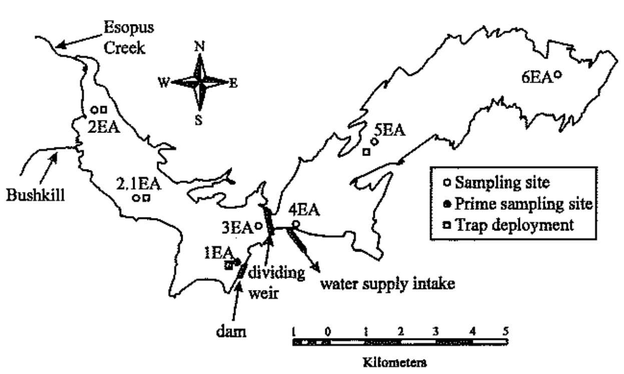

Figure 1.–Ashokan Reservoir, with sampling sites for 1996 particle/turbidity study.

Methods

Ashokan Reservoir

Ashokan Reservoir (Fig. 1), located 115 km northwest of New York City (NYC) and 81 km east of Cannonsville Reservoir, has the largest surface area and the second largest volume (Table 1) of NYC's 19 water supply reservoirs. It contributes about 40% of the water required by the city (Snopek et al. 1996). The reservoir has two basins, the east and west, which are separated by a concrete dividing weir (Fig. 1). The full capacity volume and surface area of the east basin exceed those of the west basin by factors of ~ 1.7 and 1.6, respectively (Table 1). The west basin of the reservoir has a watershed area of ~ 614 km² (Table 1). Approximately 79% of the runoff reaching this basin is delivered by Esopus Creek (Fig. 1). Additionally, Esopus Creek carries water received from the Schoharie Creek watershed (from Schoharie Reservoir via a 29-km tunnel). Bush Kill also enters the west basin, though its annual flow is only ~ 10% of Esopus Creek. The watershed for the east basin is relatively small (~ 50 km², Table 1); about 90% of the water received by this basin is from the west basin (Snopek et al. 1996).

Sediment received from the Schoharie and Esopus watersheds is of concern with respect to high turbidity

Table 1.–Morphometry and watershed areas for the two basins of Ashokan Reservoir, NY (modified from Snopek et al. 1996).

Characteristic	Ashokan west basin	Ashokan east basin
maximum volume ($\times 10^6$ m³)	179	305
maximum depth (m)	58	26
mean depth (m)	13.9	14.7
surface area (km²)	12.9	20.8
watershed area (km²)	614	50

events reported in Ashokan Reservoir (e.g., Bader 1990, Snopek et al. 1996). Soils in these watersheds are derived from sandstones and shales (Titus 1993) and are considered to be highly erodible (Bader 1990). The west basin has been described as functioning as a settling basin (Snopek et al. 1996). Water supply withdrawals are almost always from the east basin (Fig. 1; intakes at depths 24.5 and 29.0 m below the spillway elevation). Seasonal average values of T_n tend to be higher, and Secchi disc transparency lower, in the west basin, based on the results of a fixed - frequency monitoring program (e.g., NYCDEP 1993). Values of trophic state indicators such as total phosphorus (e.g., mean values of 12.4 and 11.9 $\mu g \cdot L^{-1}$ for the west and east basins, respectively, in 1992) and chlorophyll *a* (e.g., mean values of 4.7 and 4.2 $\mu g \cdot L^{-1}$ for the west and east basins, respectively, in 1992) reflect mesotrophy for both basins (e.g., NYCDEP 1993).

Sampling, Measurements, and Calculations

The results of a comprehensive short-term program conducted over a 6-week interval in June/July of 1996 are the primary focus of this study. Additionally, T_n data collected as part of New York City's Department of Environmental Protection (NYCDEP) monitoring program, at the "prime" site (1EA; Fig. 1) of Ashokan Reservoir (~ weekly in ice-free period) and at the water supply intake (~ daily) of the reservoir for the entire year, are included to place the observations of the short-term study in a longer-term perspective. Further, T_n data collected in a similar monitoring program for Cannonsville Reservoir in 1996 [the prime (site 4) reservoir site, and downstream of water supply intakes; see Effler and Bader (1998)] are presented to contrast this feature of these two reservoirs.

Samples were collected weekly for the short-term program, at seven reservoir sites (Fig. 1) incorporated in the long-term NYCDEP monitoring program, and in two streams, near the mouths of Esopus Creek and Bush Kill. Field measurements in the reservoir included temperature (°C), specific conductance ($\mu S \cdot cm^{-1}$), transmissometry, Secchi disc (SD, m), and up- and downwelling cosine irradiance (site 1EA only, Fig. 1; see Table 2 for specifications). The beam transmissometer measures the beam attenuation coefficient at 660 nm (c_{660}, m^{-1}). Values and variations of c_{660} were regulated largely by the magnitude of scattering that prevailed in the reservoir during the study. Laboratory analyses of water column samples included individual particle analysis (IPA) (Effler et al. 1998a, b), electronic particle counts, T_n (NTU), and chlorophyll (Chl,

Table 2.–Specifications for program of measurements.

Measurements	Instrument/Description/References
Field	
1. temperature, beam transmissometry	Seabird Sealogger Profiler (Model SBE 25); 8 readings s^{-1}, descent rate of 1.2 $m \cdot s^{-1}$
2. Secchi disc	20-cm-diameter black and white quadrant disc
3. up- and downwelling irradiance	cosine sensors (LI-COR 192 (z)), photosynthetically active radiation (400 - 700 nm; Effler 1998b)
Laboratory	
4. individual particle analysis (IPA)	scanning electron microscopy (ETEC AutoScan), interfaced with a X-ray spectrometer (KEVEX 7500), and a image analysis system (LeMont Scientific DA-10; SAX) sample handling and preparation according to Johnson et al. (1991)
5. electronic particle counts	HIAC/ROYCO Model 8000A eight channel variable "bin" size particle counter, with Model HRLD liquid sensor; "bin" size ranges of 1.5 - 2, 2-3, 3 - 3.9, 3.9 - 6, 6 - 7.8, 7.8 - 15.6, 15.6 - 31, > 31 μm
6. turbidity (T_n)	HACH 2100A turbidimeter (Method 2130B; APHA 1992)
7. total chlorophyll (Chl)	spectrophotometric, acetone extraction (Parsons et al. 1984)
8. total suspended solids (TSS)	gravimetric (Method 2540D; APHA 1992)

$\mu g \cdot L^{-1}$) (Table 2). Samples were collected at a depth (z) of 3 m at all reservoir sites. Additionally, except at site 1EA, samples were also collected at depths of 0, 6, 9, 12, 18, 24, 30, 36, and 41 m. Tributary samples were grab-type from the surface. Sediment trap collections were made at 2EA (z = 15 m), 2.1EA (z = 15 m), 1EA (z=28 m) and 5EA (z=24 m; Fig. 1). Deployments were for 1 week (i.e., n=5 for each site) and collections were analyzed for total suspended solids (TSS; Table 2). Traps were cylindrical and had an aspect ratio (height/diameter) of 10:1 (e.g., Bloesch and Burns 1980, Rosa et al. 1991). Other features of trap configuration and deployment were described by Snopek et al. (1996).

The application of the SAX technique for IPA (Table 2) is particularly appropriate for evaluations of the origins of inorganic particles and associated turbidity (Effler et al. 1992, Johnson et al. 1991, Yin and Johnson 1984) because it provides physical (size, shapes, and count) and chemical (elemental) characterizations of particles > 0.5 µm in diameter. Organic particles are not accurately imaged by this technique (Jiao 1991, Johnson et al. 1991). Detailed descriptions of sample preparation and analysis procedures are presented elsewhere (Johnson et al. 1991). Various particle classification schemes have been used to simplify the copious data generated by these analyses (Johnson et al. 1991, Yin and Johnson 1984). The simple scheme of six generic particle types (organic, calcium-rich, clays, iron-rich, silica, and other) applied for Cannonsville Reservoir (Effler et al. 1998a, b) has been adopted here for Ashokan Reservoir, in part to facilitate comparison. Values of the scattering coefficient (b, m^{-1}; at 10% light level) at site 1EA were calculated from analysis of up- and downwelling irradiance according to the protocol of Kirk (1981).

A runoff event of moderate magnitude (peak daily average flow of 60 $m^3 \cdot s^{-1}$ in Esopus Creek) was captured in the 6-week intensive program (Fig. 2). The first three surveys were conducted at low creek flows (< 5 $m^3 \cdot s^{-1}$). The fourth survey (July 16) was 3 days past the peak runoff of the event; the daily average flow was about 35 $m^3 \cdot s^{-1}$ for this survey (Fig. 2). The previous event (peak ~ 30 $m^3 \cdot s^{-1}$) was in early June; two major runoff events (daily average of value ~ 100 $m^3 \cdot s^{-1}$) occurred in April. The highest peak flow in 1996 occurred in January (Fig. 2; daily average of value ~ 615 $m^3 \cdot s^{-1}$). The estimated recurrence interval of this flow is 30 years. The annual flow of Esopus in 1996 was the ninth highest of the 65-year record. A maximum drawdown of only ~ 5.0 m below the dividing weir occurred on January 18, 1996.

Samples for IPA characterization were selected to examine the affects of the mid-July runoff event on particle type distributions. These included two samples from Esopus Creek (July 9 and 16), and samples on

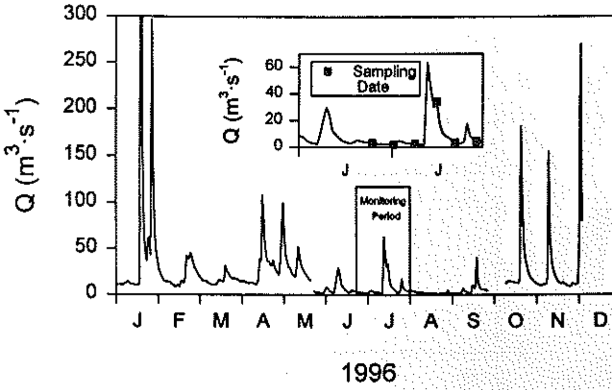

Figure 2.–Time series of daily average flows in Esopus Creek near its mouth, 1996. Time series for June and July (includes 6-week study period) presented as an inset.

4 days from the upper waters at the prime reservoir site (1EA) that bracket the runoff event. Additionally, two deep water samples collected 3 weeks apart were analyzed to contrast epilimnetic and hypolimnetic conditions. SAX results are presented here in terms of percent composition of the particle classes and the particle cross-selectional area per unit volume (PAV; e.g., Johnson et al. 1991) associated with these particle classes. Some samples were reanalyzed without the automated image analysis capabilities to assess contributions of diatoms to the silica class and the presence of organic particles. Values of T_n were estimated from PAV data (e.g., presented as T_n "model") according to procedures described by Effler et al. (1998b) that accommodate the effects of particle size on T_n. Since the particles exhibited a log normal size distribution, size has been expressed here as the geometric mean area equivalent diameter. The size adjustments in the T_n model (Effler and Perkins 1996, Effler et al. 1998b) were based on this representation of particle size. Uncertainties in the presented model T_n values represent the effects of variability in the coverage (e.g., non-uniform) of the filters used in the SAX analysis. We acknowledge other sources of uncertainty in these estimates (e.g., dependency of the T_n-PAV relationship on particle size), but expect the variability in filter coverage to be the major factor.

Results and Discussion

Esopus Creek

Increased concentrations of particles (electronic particle counter, Fig. 3b), and thereby T_n (Fig. 3c), occurred in Esopus Creek in response to the runoff event of mid-July (Fig. 3a). The PAV increased more

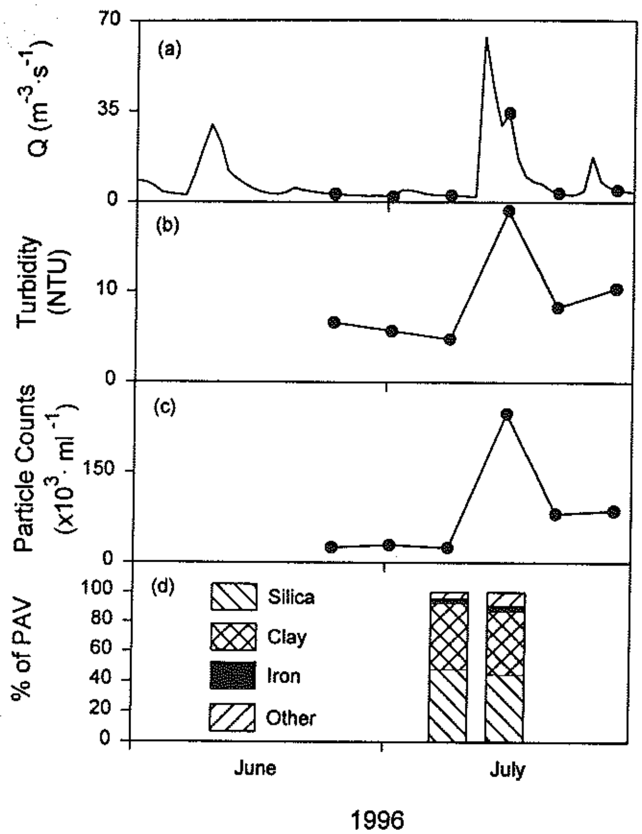

Figure 3.–Esopus Creek conditions for study period of 1996: a) daily average flow, b) turbidity (T_n), c) total particle counts (electronic particle counter), and d) contributions of particle types, according to percent of measured PAV.

than eightfold in the creek from July 9 (before the event) to July 16, and the geometric mean particle size increased from 2.1 to 3.0 µm (Table 3). The increased representation by larger particles at the elevated flow reflects the effects of increased turbulence. Conspicuous decreases in particle concentration (Fig. 3b) and T_n (Fig. 3c) were observed the following week when flow had returned to an essentially baseline, pre-event level, though a residual effect in these particle-related characteristics was observed relative to flow. The contribution from Bush Kill was insignificant by comparison; e.g., values of T_n = 0.4 and 2.9 NTU were measured on July 9 and July 16.

Despite the clear increase in particle loading from Esopus Creek in response to the runoff event (Fig. 3b and c), the distribution of particle types remained virtually unchanged in this tributary (Fig. 3d). The dominant particle types in Esopus Creek according to SAX were silica and clay (see Table 1, Effler et al. 1998a); together, these two types represented 92.5 and 87% of the PAV on July 9 and 16, respectively (Fig. 3d). Minor variations in other types of particles were statistically insignificant. Further, allochthonous inputs of organic particles were found to be low.

Modest trends in particle-type distributions as a function of size are indicated for the Esopus particle population of July 16 (Table 4). However, Chi Square homogeneity tests indicate that these size-fractionated differences are not statistically significant. Thus, it is reasonable to assume that the operation of in-reservoir particle size sorting processes (e.g., deposition) should not be expected to result in major systematic shifts in the relative contributions of particle types of allochthonous origins within the reservoir.

Table 3.–IPA results for geometric mean particle size (µm, area equivalent diameter), mean PAV (mm^2 cm^{-3}), and comparison of predicted T_n (NTU) with measured T_n (NTU) for Ashokan Reservoir samples. Uncertainties in model T_n values estimated at +/- one standard deviation.

Sample/Date	Size	PAV	T_n model	T_n measured
Esopus 7/9	2.1	0.44	3.5 ± 1.1	4.7
Esopus 7/16	3.0	3.80	19.0 ± 3.3	19.0
1EA, 3 m 7/9	2.2	0.21	1.7 ± 0.8	1.6
1EA, 3 m 7/16	2.3	0.47	2.8 ± 1.0	2.3
IEA, 3 m 7/22	2.0	0.50	5.0 ± 1.6	4.7
1EA, 3 m 7/29	2.1	0.40	3.3 ± 0.6	2.7
1EA, 24 m 7/9	1.7	0.59*	9.4	20.2
1EA, 24 m 7/29	1.9	0.19*	2.4	10.9

* accurate image analysis for PAV measurements not possible - see details in text.

Table 4.–Generic particle-type contributions (%) of measured PAV in the Esopus Creek July 16 IPA sampling as a function of particle size. Column entries are normalized to the fraction of PAV contributed by particles less than or equal to the indicated size (μm, area equivalent diameter).

Generic Class	24 μm	12 μm	9 μm	6 μm	4.5 μm
Organic	1.8	3.0	2.8	2.3	3.7
Ca Aggregate	2.8	0.4	0.4	9.8	1.3
Ca Only	0	0	0	0	0
Clay	42.5	36.6	37.6	33.8	30.2
Iron	4.4	4.8	5.6	3.6	4.4
Silica	44.9	52.8	51.4	56.6	57.8
Miscellaneous	3.6	2.4	2.2	2.9	2.6

In-Reservoir Patterns

Specific Conductance, Transmissometry, Turbidity, Deposition

Several features of the signatures imparted by the event in the west basin are evaluated here within the context of vertical profiles collected for 3 consecutive weeks that bound the runoff event. The sample sites within the west basin remained stratified through the runoff event, though stratification was eroded at the upstream station (2EA) by the hydrologic inputs (Fig. 4). Clear signatures of sub-surface dilution from the event were imparted in the profiles of specific conductance on July 16 (Fig. 5). The magnitude of the effect diminished from upstream (site 2EA) towards the dam. This dilution effect of the runoff event is consistent with long-term monitoring data collected by NYCDEP at the mouth of Esopus Creek; e.g., lower specific conductance values are generally observed at higher flows (see also Smith et al. 1996). An analysis of 367 paired observations of specific conductance (grab-type samples) and daily average flow (Q, $m^3 \cdot s^{-1}$) resulted in the following linear inverse-flow (by linear least squares regression) relationship ("dilution model," see Effler et al. 1996)

$$\text{specific conductance } (\mu S \cdot cm^{-1}) = 133 \cdot Q^{-1} (m^3 \cdot s^{-1}) + 55.9 \; (R^2 = 0.38) \quad (1)$$

The vertical position(s) of the dilution effect (Fig. 5) indicates runoff during the event entered the reservoir water column as an interflow (LaBounty and Horn 1997, Thornton et al. 1990), above the hypolimnion (Fig. 4). Apparently the stream was more dense than the reservoir surface waters during the runoff event, associated with the elevated suspensoid concentrations and perhaps lower temperature of the creek (Wetzel 1983). The occurrence of the interflow phenomenon was promoted by the highly structured antecedent stratification of the west basin (Fig. 4).

Entry of the elevated particle loads (Fig. 3b and c) as an interflow was manifested as sub-surface peaks in c_{660} at all sites at a depth (z) of about 9 m in the west basin (Fig. 6). The sub-surface peak in T_n is less clearly resolved (Fig. 7) because of the large depth interval of sampling (3 m) for this analyte. Longitudinal structure

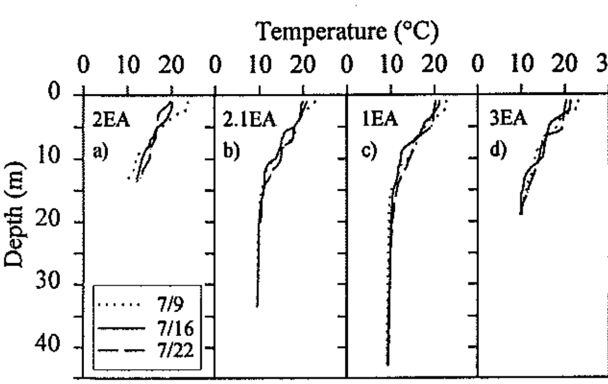

Figure 4.–Thermal stratification in the west basin of Ashokan Reservoir for 3 days bounding the July runoff event of 1996: a) 2EA, b) 2.1EA, c) 1EA, and d) 3EA.

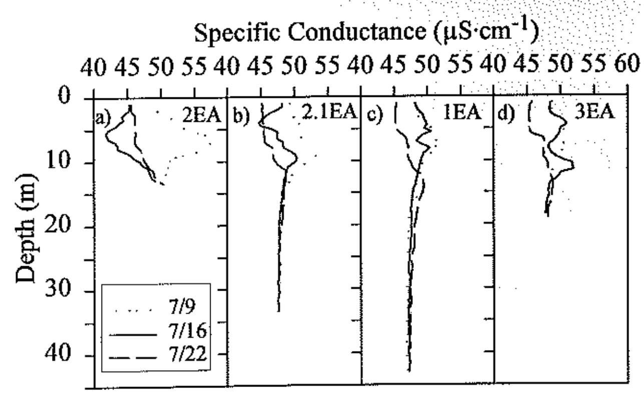

Figure 5.–Vertical profiles of specific conductance in the west basin of Ashokan Reservoir for 3 days bounding the July runoff event of 1996: a) 2EA, b) 2.1EA, c) 1EA, and d) 3EA.

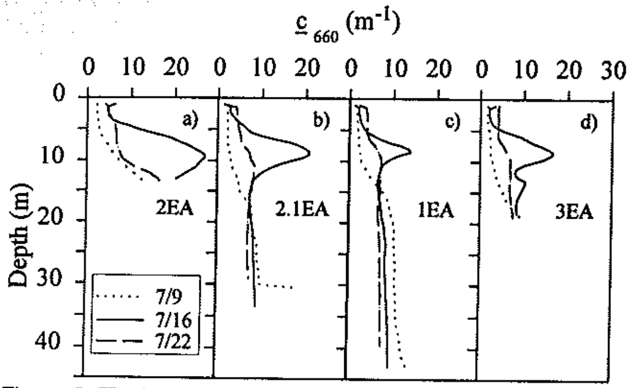

Figure 6.–Vertical profiles of $\underline{c}_{660}$ in the west basin of Ashokan Reservoir for 3 days bounding the July runoff event of 1996: a) 2EA, b) 2.1EA, c) 1EA, and d) 3EA.

in sub-surface c_{660} on July 16 tracked that observed for specific conductance; e.g., the signal diminished from upstream portions of the basin (Fig. 6a) toward the dam (Fig. 6c and d). The July 16 profile at site 3EA establishes the sub-surface (interflow) particle plume formed from the Esopus Creek input reached the dam in about 3 days following the peak of the runoff event. These findings are consistent with those reported by Snopek et al. (1996). They found a subsurface "turbidity" plume associated with a runoff event in October 1995 reached the dam in less than 3 days. Note that the vertical structures of specific conductance (Fig. 5), c_{660} (Fig. 6), and T_n (Fig. 7) imparted from the interflow of the mid-July runoff event were largely absent 6 days later, as a result of mixing within the epilimnion over that interval. Specific conductance decreased (Fig. 5), and c_{660} (Fig. 6) and T_n (Fig. 7) increased in the surface waters throughout the epilimnion of the west basin as a result of the mid-July runoff event (compare profiles of July 9 and 22).

The dynamics of the estimates of the scattering coefficient, b, approximately tracked those measured for T_n (z = 3 m) at site 1EA (linear least squares regression expression, with y-intercept = 0; $T_n = 0.70 \cdot b$, $R^2 = 0.76$). The non-uniform distribution of particles over depths above the 10% light level at times during the study (see Fig. 7) probably contributed to the observed modest disparity in T_n and b. The SD value was observed to be inversely related to T_n. The relationship has been described elsewhere (Effler 1988) by

$$SD = N''/T_n \tag{2}$$

According to linear least squares regression (y-intercept = 0), using paired observations of SD and T_n (z = 3 m) for all reservoir sites, the value of N" equals 5.2 ($R^2 = 0.79$) within the range reported by Effler (1988). The average SD values for the west and east basins (all sites) for the 6-week study were 2.0 and 4.25 m, respectively; the ranges were 1.1 (site 2EA) to 3.9 (site 3EA), and 2.2 (site 4EA) to 4.95 m (sites 5EA and 6EA), respectively.

The partitioning of the contributions of phytoplankton and inorganic tripton to T_n has been described by (Effler et al. 1998b)

$$T_n = K_b \cdot Chl + T_n' \tag{3}$$

where T_n' = turbidity associated with inorganic tripton, K_b = chlorophyll-specific turbidity value, and Chl = concentration of chlorophyll. The average Chl values for the west and east basins (all sites) for the 6-week study were 4.1 and 4.0 $\mu g \cdot L^{-1}$, respectively. Based on a reasonable range of K_b values (e.g., 0.05 to 0.15 NTU $\cdot m^3 \cdot mg^{-1}$ Chl, assumes $T_n = b$; Effler et al. 1998b, Weidemann and Bannister 1986) and observations of Chl from site 1EA, inorganic tripton represented >75% of T_n throughout the 6-week study period. In contrast, phytoplankton represented a larger fraction of T_n in the east basin, perhaps accounting for as much as 50% of T_n in the east basin (site 5EA) in mid-July (Chl = 5 to 8 $\mu g \cdot L^{-1}$).

The patterns in T_n imparted within the epilimnion (z = 3 m) along the main axis of the reservoir in response to the runoff event were quite distinct, when

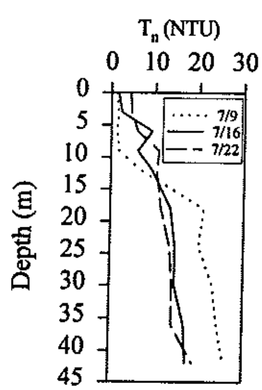

Figure 7.–Vertical profiles of T_n in the west basin (site 1EA) of Ashokan Reservoir for 3 days bounding the July runoff event of 1996.

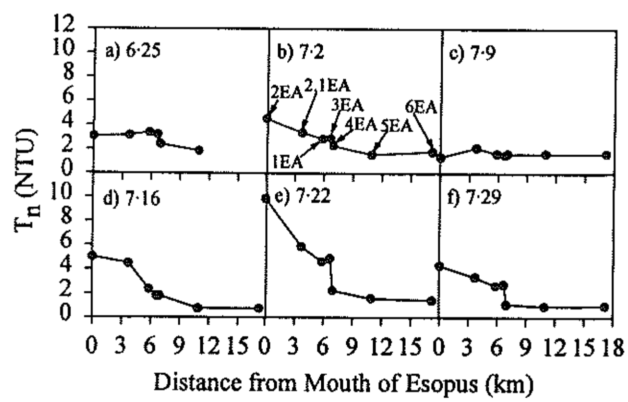

Figure 8.–Longitudinal patterns of T_n in Ashokan Reservoir for 6 days in the summer of 1996: a) June 25, b) July 2, c) July 9, d) July 16, e) July 22, and f) July 29.

viewed as longitudinal profiles (Fig. 8). Turbidity values were greater in the west basin than in the east for the first two surveys, but longitudinal differences were minor for the (third) survey before the runoff event (Fig. 8a-c). The longitudinal gradient was conspicuous in the west basin 3 days after the peak flow of the runoff event (Fig. 8d). The gradient was even more distinct at this depth for the fifth survey (Fig. 8e) because of the vertical mixing of the interflow with overlying layers (see Figs. 6c and 7) over the intervening 6 days. This longitudinal signal had diminished substantially by the last survey of the study (Fig. 8f). The east basin remained relatively unaffected by this moderate runoff event (Fig. 8).

Values of c_{660} and T_n were substantially higher in the hypolimnion than the epilimnion at the start of the study. The progressive increases observed with the approach to the sediments are indicative of a nepheloid layer (Halfman and Johnson 1989, Effler et al. 1998a). In contrast to the epilimnetic temporal pattern, progressive decreases in c_{660} (Fig. 6c) and T_n (Fig. 7) occurred in the hypolimnion over the 6-week study period, indicating depositional inputs from the July runoff event were not a major factor in these lower layers. These temporal and vertical patterns for the hypolimnion are most likely in response to particle inputs received with the larger runoff events of winter and spring (Fig. 2). Note that the lower specific conductance values of the hypolimnion are qualitatively consistent with this position. The water that filled the reservoir in late spring before the onset of density stratification had relatively low specific conductance associated with high Esopus Creek flows [Fig. 2 and Eq. (1)]. Subsequently, the specific conductance of the epilimnion increased as a result of the inflow of warmer water that had higher specific conductance associated with the lower tributary flow [see Eq. (1)], producing the vertical structure encountered at the start of the 6-week study period (e.g., Fig. 5).

The influence of external particle loading supplied by Esopus Creek is also evident in the longitudinal and temporal patterns of TSS deposition (Fig. 9). Increases in deposition were observed in the west basin in response to the runoff event. Further, the magnitude of the deposition flux decreased progressively away from the mouth of the Esopus Creek tributary (site 2EA) over the 6-km distance to the prime sampling site (1EA) where the flux was only about 20% of that measured at site 2EA. By comparison, deposition in the east basin was much lower, averaging (at site 5EA) only about 20% of that observed at the prime sampling site (1EA) of the west basin.

Review of paired time series of Esopus Creek flow and T_n in the upper waters at site 1EA and in the water supply withdrawal for all of 1996 (Fig. 10a-c) indicates particle loadings received from the creek during runoff events repeatedly caused elevated T_n values. The dynamics of T_n in the withdrawal (Fig. 10c) were particularly responsive to runoff events in periods other than summer stratification. The peak T_n value of ~ 150 NTU occurred at the intake at the end of January (Fig. 10c) after the two major runoff events of that month (Fig. 10a). Turbidity values of greater than 50 NTU persisted in the withdrawal from late February through April (Fig. 10c), probably maintained by several substantial spring runoff events (e.g., peak flows (80 $m^3 \cdot s^{-1}$, Fig. 10a). The thermally based density stratification of summer (e.g., Fig. 4) apparently discourages full manifestation of external particle loads at the water supply intake(s) of the east basin. For example, progressive decreases in T_n occurred from May through September at the intake despite the substantial runoff events of June and mid-July, and the very distinct signature imparted in the west basin following this later event (Fig. 10b; also see Figs. 6-9). The levels of T_n in both the west basin and at the intake were highly responsive to particle loads received during

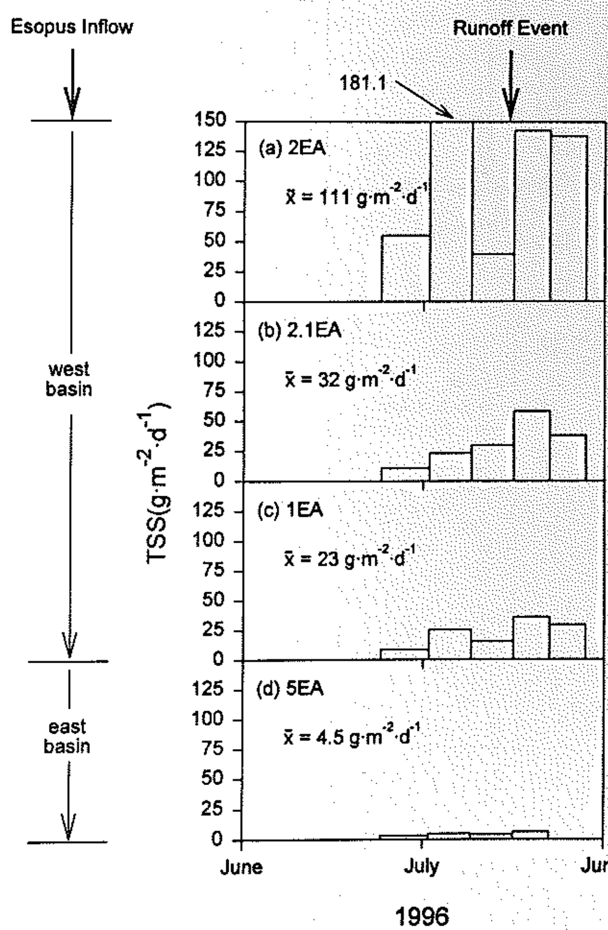

Figure 9.–Temporal and spatial patterns in TSS deposition rate in Ashokan Reservoir during the study period of 1996: a) 2EA, b) 2.1EA, c) 1EA, and d) 5EA.

three runoff events [peak flows (150 $m^3 \cdot s^{-1}$) from late October through early December (Fig. 10)], when turnover conditions typically prevail in the reservoir. Starting in mid-December, values of T_n at site 1EA and the intake tracked each other rather closely (Fig. 10b and c). Turbidity values of more than 25 NTU were observed at both locations in December.

Cannonsville Reservoir (the subject of most of this issue of the journal) responded quite differently to a very similar pattern of inflow from its largest tributary, the West Branch of the Delaware River (WBDR, Fig. 10). High sediment loads are delivered by WBDR during runoff events (Longabucco and Rafferty 1998). The level of T_n in the surface waters of Cannonsville Reservoir remained much lower (e.g., < 5 NTU) than observations at Ashokan Reservoir (Fig. 10b). No intake T_n data are available for Cannonsville Reservoir following the January events (Fig. 10c) as this impoundment was not used for water supply over this interval. The T_n value at the start of February (~ 15 NTU) was unusually high for this reservoir (e.g., Effler et al. 1998b, NYCDEP 1993), apparently in response to the antecedent high runoff, but much lower than levels in Ashokan Reservoir (Fig. 10c). Thereafter T_n decreased progressively through May in Cannonsville Reservoir, an interval through which substantial structure was observed in Ashokan Reservoir (Fig. 10c). This comparison indicates Ashokan Reservoir is much more susceptible to short-term (e.g., rapid response) turbidity-based degradation from sediment loads delivered by runoff events than Cannonsville Reservoir. Interestingly, particles of allochthonous origins also dominate turbidity in Cannonsville Reservoir under conditions of a major drawdown. However, most of these particles enter the water column through the process of resuspension (Effler et al. 1998a). We cannot discount the possibility that the sediment resuspension process has similar importance to turbidity in Ashokan Reservoir during major drawdown (e.g., dry years) intervals, nor that this process is significant during full reservoir periods. Detailed analyses during such intervals would be required to evaluate this process in this system.

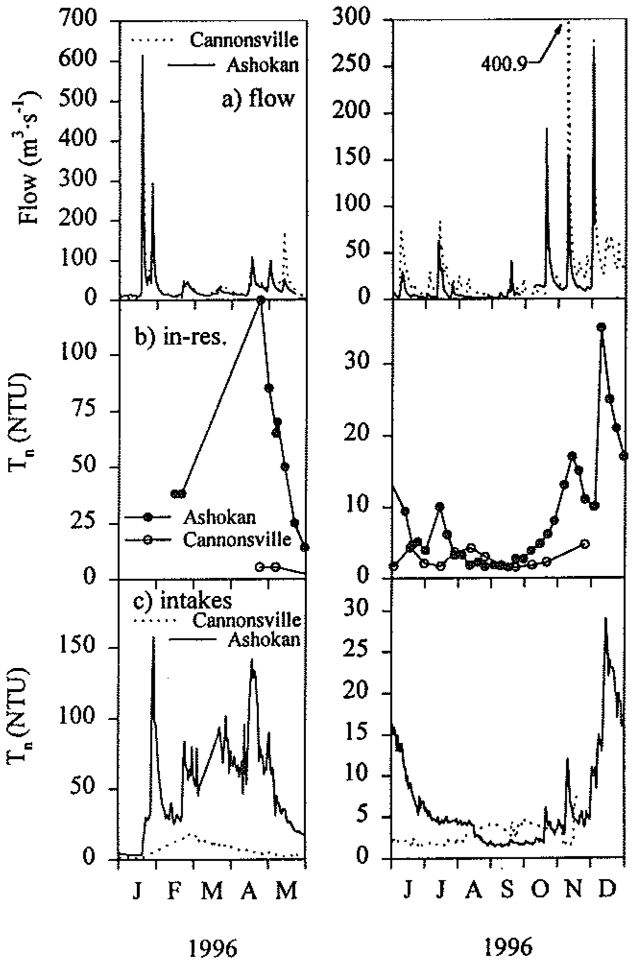

Figure 10.–Comparisons for Ashokan Reservoir and Cannonsville Reservoir for 1996: a) time series of daily average flows in the mouth of Esopus Creek and West Branch of the Delaware River upstream of Cannonsville Reservoir, b) T_n in the near-surface waters at site 1EA of Ashokan Reservoir and site 4 (see Effler and Bader 1998) of Cannonsville Reservoir, and c) T_n in the water supply withdrawals of the two reservoirs.

IPA/SAX

The composition of the particle assemblage in the epilimnion at the prime site closely tracked that of Esopus Creek over a 4-week interval that bounded the event (Fig. 11a versus Fig. 3d); according to the Chi Square homogeneity test, the chemical signatures of the creek and the reservoir were essentially the same. Only a very slight shift to larger size particles was indicated at this site in response to the runoff event, despite the conspicuous shift observed in Esopus Creek (Table 3). This indicates there was a preferential loss of larger particles supplied by the creek in upstream portions of the west basin of the reservoir, consistent with the known dependence of the settling velocity of particles on their size (Bloesch and Burns 1980) and the observed (Fig. 9) longitudinal distribution of solids deposition measured during the study. Further, the dynamics of T_n predicted from the measured PAV and particle-size distributions matched the observations of the epilimnion well (Table 3). These SAX results strongly support the position that the increases in T_n observed in the epilimnion at site 1EA following the mid-July runoff event were largely a result of increases in inorganic tripton received during the event from Esopus Creek. We estimate, based on the SAX results, that at least 85% of the T_n measured at the prime site in the epilimnion during the study was due to particles of terrigenous (allochthonous, watershed) origin. This is consistent with the partitioning estimate presented

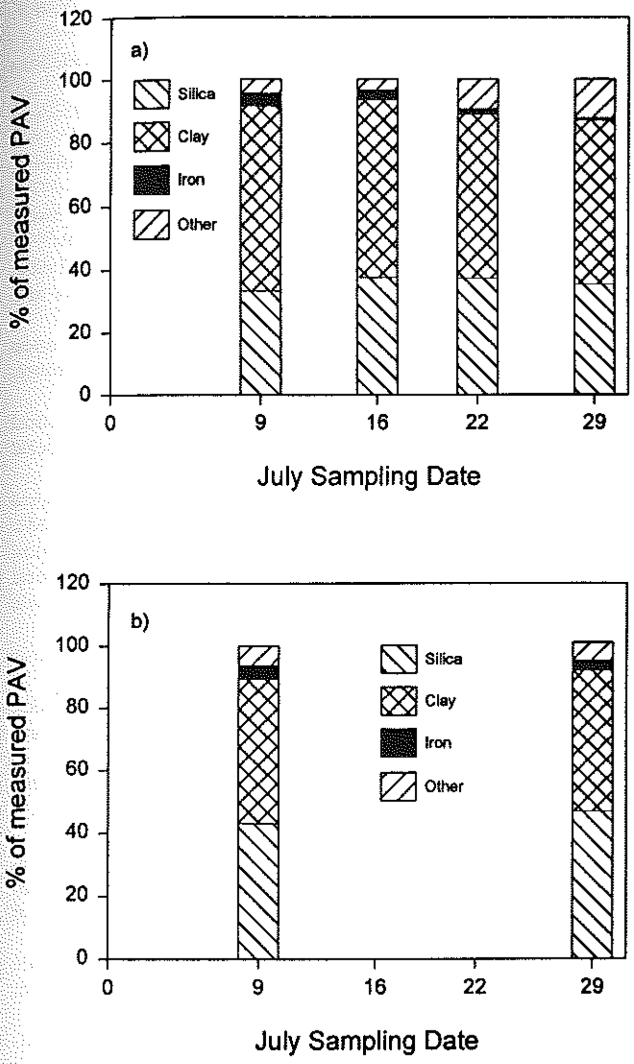

Figure 11.–Contributions of particles types to percent of measured PAV during study period, for two depths of site 1EA: a) 3 m, and b) 24 m.

previously, based on Eq. (3). For example, diatoms (an autochthonous contribution to T_n) may be included in the silica particle class (cannot be separated from quartz by SAX, also see Effler et al. 1998b). However, visual examination (minus the automated image analysis) indicated less than one-third of the silica particle class could be attributed to diatoms, and contributions by organic particles were small (< 3.5% of PAV).

The underprediction of T_n from SAX PAV data for hypolimnion samples (Table 3) prompted qualitative (manual) re-analysis (minus the automated image analysis) of these samples. The samples were found to contain large numbers of small organic detrital particles that the SAX technique systematically under-represents (e.g., Jiao 1991, Johnson et al. 1991). This is illustrated here by digital images (at 1000x magnification) from the prime sampling site at a depth of 24 m on July 29. The "plate" on the left (Fig. 12a) is the backscatter electron signal (Johnson 1983, Johnson et al. 1991); grey areas are the polycarbonate membrane and filter pores appear black. The same field of view with the secondary electron signal (Johnson 1983, Johnson et al. 1991) shows the inorganic particles and a heavy loading of organic (e.g., detrital) particles (Fig. 12b). The origins and nature of this organic material are presently unknown. The apparently important contribution of these organic particles to the T_n of the lower layers is consistent with a prolonged hypolimnetic signal of inputs to the reservoir (e.g., Fig. 6), based on their small size and lower (relative to inorganic tripton) density. These particles may have entered the reservoir in earlier events (Fig. 2; and still had not settled out), or have been resuspended from the bottom. The origins of the deep-water concentrations of organic particles in the reservoir deserve further research.

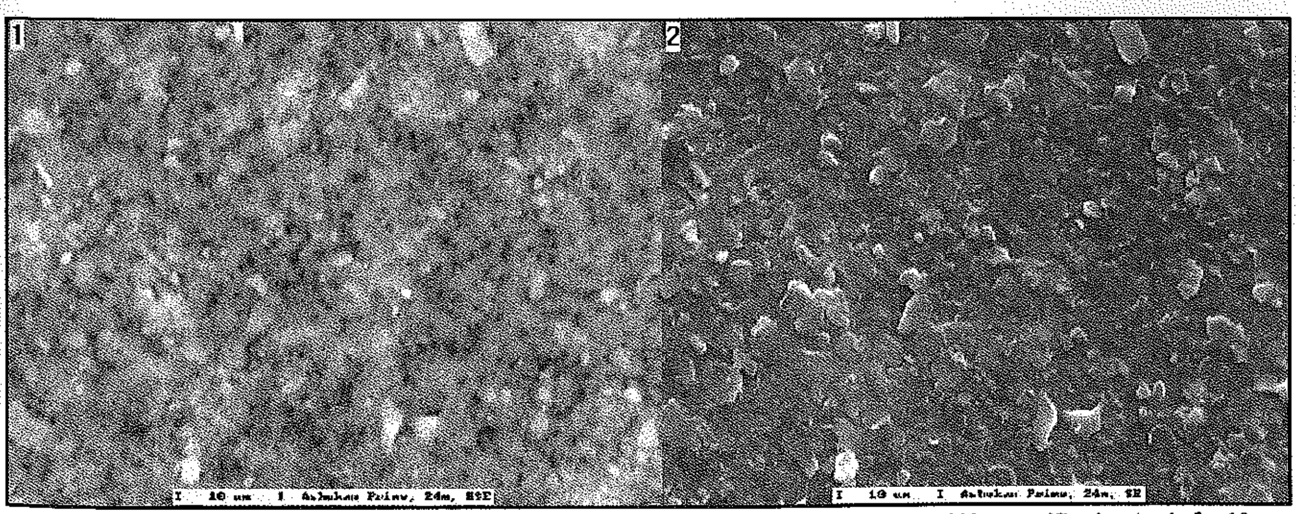

Figure 12.–Ashokan site 1EA, 24 m, July 29, 1996, digital images of particles on filter membrane at 1000x magnification (scale for 10 μm included on bottom of plates): a) backscatter electron image (left), and b) normal secondary electron image (right).

Management Perspectives

The runoff event of mid-July 1996 caused a major influx of inorganic tripton into Ashokan Reservoir. This external load of tripton, made up mostly of clays and quartz, imparted clear signatures (increases) in turbidity and deposition in time and space in the upper waters of the west basin of the impoundment. These signatures offer an excellent opportunity for testing a deterministic particle/turbidity model. Application of an individual particle analysis technique established that more than 85% of the turbidity in the upper waters at the prime monitoring site of the west basin was due to particles received from the watershed; i.e., phytoplankton represented only a modest fraction of the turbidity. The east basin remained relatively unaffected by the event. The higher turbidities of the hypolimnion in the west basin were apparently a manifestation of inputs received from earlier events. Review of monitoring data for the entire year establishes high turbidities are routinely observed in the upper waters of the reservoir following runoff events, and in the water supply intake(s) for events that occur outside of the summer stratification period.

A credible deterministic model for turbidity would be an invaluable management tool for this reservoir, and other reservoirs with turbidity problems, to evaluate the reductions in sediment loading and/or operational schemes necessary to meet specified goals/standards. The development and testing of a deterministic particle/turbidity model are recommended to provide a quantitative tool to guide the management of the turbidity problem in Ashokan Reservoir. Management action(s) should focus on reduction of the external loading of particles delivered during runoff events. Streambank stablization in the watershed is now being pursued as a way of reducing the load.

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