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Primary productivity in receiving reservoirs: links to influent streams

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Abstract. Primary productivity and chlorophyll *a* concentrations were measured in 8 reservoirs in New York City drinking-water-supply watersheds. The light-and-dark bottle O_2-change procedure was used to measure gross primary productivity (GPP) once each summer from 2000 to 2002. GPP normalized for photosynthetically active radiation (PAR) in the Neversink and Schoharie averaged only 0.025 and 0.035 g O_2/mol quanta, respectively. Values for New Croton and Cannonsville averaged 0.118 and 0.125 g O_2/mol quanta, respectively. Values in the other reservoirs (west basin Ashokan, Pepacton, Rondout, and Kensico) were intermediate. Chlorophyll *a* concentrations in reservoir photic zones ranged from mean values of <10 to 100 mg/m^2, with highest values in New Croton and Cannonsville and lowest concentrations in Neversink, Pepacton, and Schoharie. Cannonsville was eutrophic, and New Croton was at the mesotrophic–eutrophic boundary. Neversink, Schoharie, and Pepacton were at the oligotrophic–mesotrophic boundary, and the remaining reservoirs (Kensico, Rondout, and west basin Ashokan) were mesotrophic. Reservoir conditions were related to watershed-scale land use. Gradients within reservoirs in chlorophyll *a*, depth of photic zone, and primary productivity indicated an influence of the major tributary on reservoir conditions in several of the reservoirs.

Key words: phytoplankton, algae, New York City drinking-water supply, land use.

The streams and rivers draining watersheds both west and east of Hudson River feed 19 linked reservoirs and controlled lakes that store New York City's (NYC) drinking water. The largest of these storage bodies are located west of Hudson River (WOH) in the Catskill mountains (~90% of the supply), and the others are found east of Hudson River (EOH) in the Croton watershed (~10% of the supply), although these percentages can vary under drought conditions. Water is delivered to EOH reservoirs from WOH watersheds by 1 of 2 routes. In the first, an interbasin transfer tunnel collects Schoharie water (WOH) and drains to the Ashokan (WOH), which then drains to the Kensico (EOH) through the Catskill aqueduct (National Research Council 2000). In the other, 3 tunnels transfer water from the Pepacton, Neversink, and occasionally the Cannonsville to the Rondout (all WOH), and the 169-km-long Delaware aqueduct connects the Rondout to the West Branch reservoir and ultimately the Kensico (both EOH). The reservoirs are points of integration for hydrologic and watershed inputs of nutrients and contaminants, as well as sites for generation of particles through phytoplankton primary productivity. Therefore, they were included as study sites in a large-scale enhanced water-quality monitoring project (the Project) that surveyed NYC drinking-water sources (Blaine et al. 2006).

NYC drinking water from the Catskills is presently unfiltered, and major watershed-scale remediation efforts are underway to maintain a low level of suspended particulate matter in the entire supply. Phytoplankton productivity is a significant source of internally generated particles, at least seasonally, and reflects, in large measure, the input of dissolved nutrients from the watershed. In addition to affecting suspended particulate loads, algal populations affect water quality in other ways. Some Cyanobacteria and diatom species can cause taste and odor problems; algal excretion products increase dissolved organic C concentrations and, thus, the potential for production of disinfection by-products (Latifoglu 2003); and some Cyanobacteria taxa are capable of producing toxins. Algal blooms increase hypolimnetic O_2 demand when

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they decay and, when severe, can result in anoxic conditions. A considerable amount of physical and chemical data has been published for some of the reservoirs studied in the Project, particularly the Cannonsville (e.g., Effler and Bader 1998). However, except for chlorophyll data, little biological information on the reservoirs has been published in the peer-reviewed literature. Similarly, except for a model of phytoplankton growth in the Cannonsville reservoir (Auer and Forrer 1998), few data concerning ecosystem processes such as primary productivity have been published for these reservoirs. Thus, our goal was to evaluate reservoir condition using algal biomass and phytoplankton productivity as response variables in this synoptic survey of NYC source waters.

Primary productivity and algal biomass were measured in 8 reservoirs: Cannonsville, Pepacton, Neversink, Rondout, Schoharie, and the west basin of the Ashokan (all WOH) and New Croton and Kensico (both EOH) during the summers of 2000, 2001, and 2002. If the major tributary to a reservoir were the principal source of nutrients, we hypothesized that: 1) gradients of productivity and algal biomass would occur within the reservoir, and 2) links between stream productivity (Bott et al. 2006), nutrient supply (Newbold et al. 2006), and reservoir productivity might be evident. In addition, these data were collected to provide a baseline for comparison with data collected in the future.

Methods

Study sites

Reservoirs included in this study with the largest storage capacities were the Cannonsville and Pepacton, and reservoirs with the smallest capacities were the Schoharie and New Croton (National Research Council 2000; Table 1). Water residence time was shortest in the Kensico (a storage and mixing reservoir) and longest in the Pepacton. NH_4^+ concentrations were highest in Ashokan, Cannonsville, and Schoharie (presumably reflecting agricultural activity in their watersheds and the transfer of Schoharie water to the Ashokan; Table 1). Total dissolved P (TDP) and soluble reactive P (SRP) concentrations were higher in the Ashokan than in the other reservoirs at the time of our studies. Total alkalinity was greatest in the New Croton, reflecting the different geology between EOH and WOH regions (Dow et al. 2006). The Kensico also is located EOH but receives most of its water from WOH reservoirs and, thus, had a total alkalinity similar to WOH reservoirs. Dissolved organic C (DOC) concentrations were greatest in the New Croton, reflecting a similar difference in DOC between WOH and EOH streams (Kaplan et al. 2006).

Three locations (substations [SS]) were established on each reservoir (Figs 1 and 2). The location of each SS was fixed using GPS during the second year of work. Those data are available in a summary report (http://www.stroudcenter.org/research/nyproject; SWRC 2003).

Field procedures

Phytoplankton productivity and community respiration in each reservoir were measured on one day each summer from 2000 to 2002. The earliest measurement date was 20 June; the latest was 19 September (Table 1). One day before measuring productivity, photosynthetically active radiation (PAR) was measured at successive 0.5-m increments through the water column, coupled with simultaneous measurements made above water, to establish the depth of the photic zone (to 1% of surface PAR) at each substation. A spherical underwater quantum sensor and a quantum sensor for use in air were used with a LI-Model 1400 light meter (LI-COR, Lincoln, Nebraska) for these measurements, which were made as close to midday as possible. Dissolved O_2 and temperature profiles at each SS were determined using a YSI model 5739 probe and model 58 meter (Yellow Springs Instruments, Yellow Springs, Ohio) in 2001 and 2002.

The next day, primary productivity was measured using dissolved O_2 changes in light and dark bottles. In 2001 and 2002 measurements were made only on bright days when objects cast distinct shadows, which was also the case for most (but not all) reservoirs in 2000. Incubations were conducted during the 4.5 to 6 h around solar noon. Water was collected using Van Dorn samplers from just beneath the water surface and at depths where PAR was 50%, 25%, 10%, and 1% of incident light. Water (12–15 L) from a given depth was pooled and bubbled with N_2 for ~6 min to reduce the dissolved O_2 saturation (often >95%) to between 70 and 80% (a step usually not required for water from the 1% intensity depth). It was assumed that the concentration of dissolved CO_2 was not affected by this step because pH did not change measurably. Biological oxygen demand (BOD) bottles (2 light and 1 dark) used for incubations were rinsed 3 times with water from depth, immersed in that water to bring the bottle to temperature at depth, filled (without introducing bubbles), stoppered, and transferred to a holding bath in a shaded location on the boat. Water temperature, dissolved O_2 concentration, and O_2 % saturation were measured in each bottle using a YSI model 58 meter and model 5905 probe with stirrer. Each bottle was topped off with 0.5 to 1 mL of reserved pooled water, resealed, and replaced in a holding bath. The process was repeated with water collected from each depth. After bottles from all depths were prepared, they were placed horizontally in clear acrylic holders (Wetzel and Likens 1991) and suspended in the reservoir at the appropriate depth. The entire process was repeated at each substation. After incubation, dissolved O_2 concentration, O_2 % saturation, and water temperature were remeasured in each bottle. During the incubation period, above-water PAR was measured from the boat deck. Between reservoirs, BOD bottles were filled with a 30% bleach solution for 15 min, rinsed, and air-dried to kill attached microbes.

A 2-L sample of water from each depth was collected for analysis of phytoplankton chlorophyll *a*. Samples were iced immediately, filtered onto GF/F filters within 24 h, and stored frozen until extraction. Other samples of surface water were filtered through precombusted Gelman GF/F filters (250 mL for inorganic nutrient analyses and 40 mL for DOC). Samples for inorganic nutrient analyses were placed on ice until they could be frozen in the laboratory; DOC samples were fixed with 0.27 mM azide and refrigerated. Additional water was collected directly into 125-mL bottles (leaving no head space), iced, and later refrigerated for total alkalinity determinations.

Laboratory analyses

Chlorophyll *a* was analyzed spectrophotometrically with correction for pheophytin according to Lorenzen (1967). The frozen filters were macerated in a 90% acetone/10% saturated $MgCO_3$ solution (Method 10200H; APHA 1998) at 4°C, extracted in a freezer for 16 to 24 h in darkness, and centrifuged at 8000 × *g* for 20 min at 4°C. All manipulations were done on ice and in subdued light to prevent photobleaching of pigments. To insure complete extraction, samples were re-extracted until the OD_{665} before acidification was ≤ 0.1 absorbance units or $\leq 10\%$ of the absorbance in the initial extraction. Water-chemistry analyses were done using procedures documented in Newbold et al. (2006) and Kaplan et al. (2006).

Data analyses

Estimates of gross primary productivity (GPP) were obtained by summing dissolved O_2 change in each light bottle with the change in the dark bottle at that depth. The mean value for each depth was integrated to the midpoint between incubation depths and summed to generate an estimate of area-specific productivity over the photic zone at each substation. SS data were averaged for each reservoir. Chlorophyll *a* concentrations were integrated similarly.

Reservoir trophic status was assessed by comparison with published criteria based on chlorophyll *a*

TABLE 1. Physical and chemical characteristics of 8 reservoirs in the New York City source-water watersheds east of Hudson River (EOH) and west of Hudson River (WOH). Historical data for reservoir storage capacity and water residence time were obtained from the National Research Council (2000), except as indicated. Water chemistry, light, and temperature data are means of data collected on 3 measurement dates during the summers of 2000, 2001, and 2002. TDP = total dissolved P, SRP = soluble reactive P, DOC = dissolved organic C, TA = total alkalinity, PAR = photosynthetically active radiation, Ashokan = west basin of the Ashokan Reservoir.

Reservoir	Storage capacity (10^6 m^3)	Water residence time (mo)	NH_4-N (mg/L)	NO_3-N (mg/L)	TDP (mg/L)	SRP (mg/L)	DOC (mg/L)	TA (mg/L)	Hourly mean PAR (mol quanta)	Mean temperature (°C)	Measurement date (Julian day)		
											2000	2001	2002
WOH													
Ashokan	178.7	2.4	0.017	0.096	0.006	0.005	2.17	10.47	3.13	21.09	19 Sept (262)	28 Aug (240)	26 June (177)
Cannonsville	366.1	5.16	0.015	0.083	0.004	0.002	2.83	16.2	4.69	24.33	9 Aug (221)	23 Aug (235)	17 July (198)
Neversink	134.2	5.04	0.006	0.085	0.004	0.002	1.96	2.68	4.91	20.36	13 Sept (256)	12 July (193)	1 Aug (213)
Pepacton	543.9	8.52	0.005	0.016	0.003	0.002	1.88	10.72	4.54	21.92	17 Aug (229)	9 Aug (221)	2 July (183)
Rondout	189.4	1.68	0.008	0.105	0.004	0.002	2.11	8.91	3.66	21.20	26 July (207)	10 July (191)	30 July (211)
Schoharie	74.2	1.2	0.011	0.062	0.003	0.001	2.17	17	5.43	21.92	6 Sept (249)	31 July (212)	20 June (171)
EOH													
Kensico	115.8	0.72	0.005	0.075	0.003	0.001	2	12.5	3.74	20.79	23 Aug (235)	20 June (171)	5 Sept (248)
New Croton	71.9	2.4^{a}	0.007	0.043	0.004	0.002	4.33	51.28	4.73	24.94	30 Aug (242)	3 July (184)	14 Aug (226)

[a] From NYC DEP (2002)

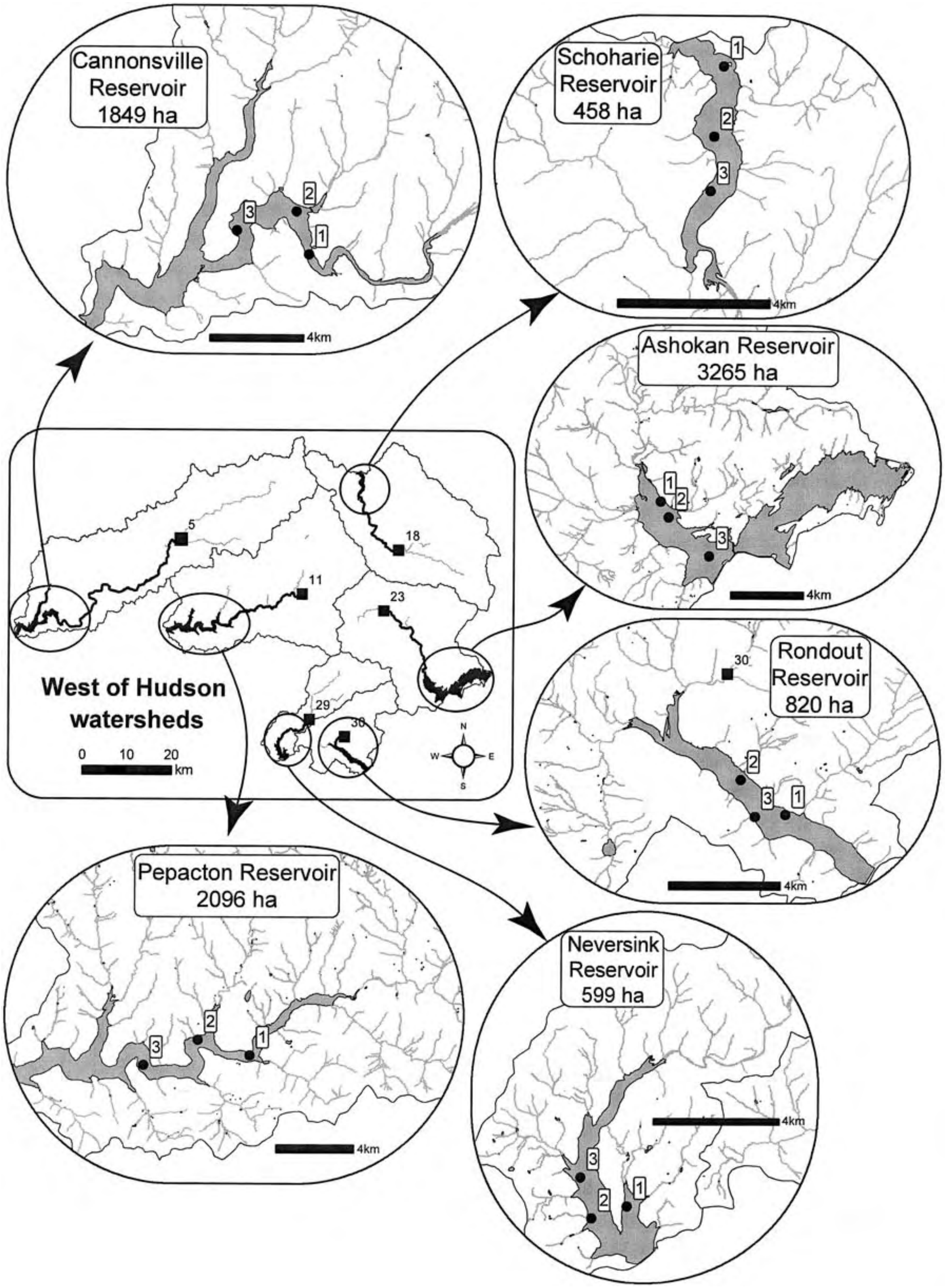

FIG 1. Reservoirs in the west of Hudson River (WOH) watersheds. Reservoir study substations are indicated in each inset and integrative stream sampling sites (Blaine et al. 2006, Bott et al. 2006) are indicated (with site numbers; see figs 1 and 2 in Arscott et al. 2006) on the WOH regional map.

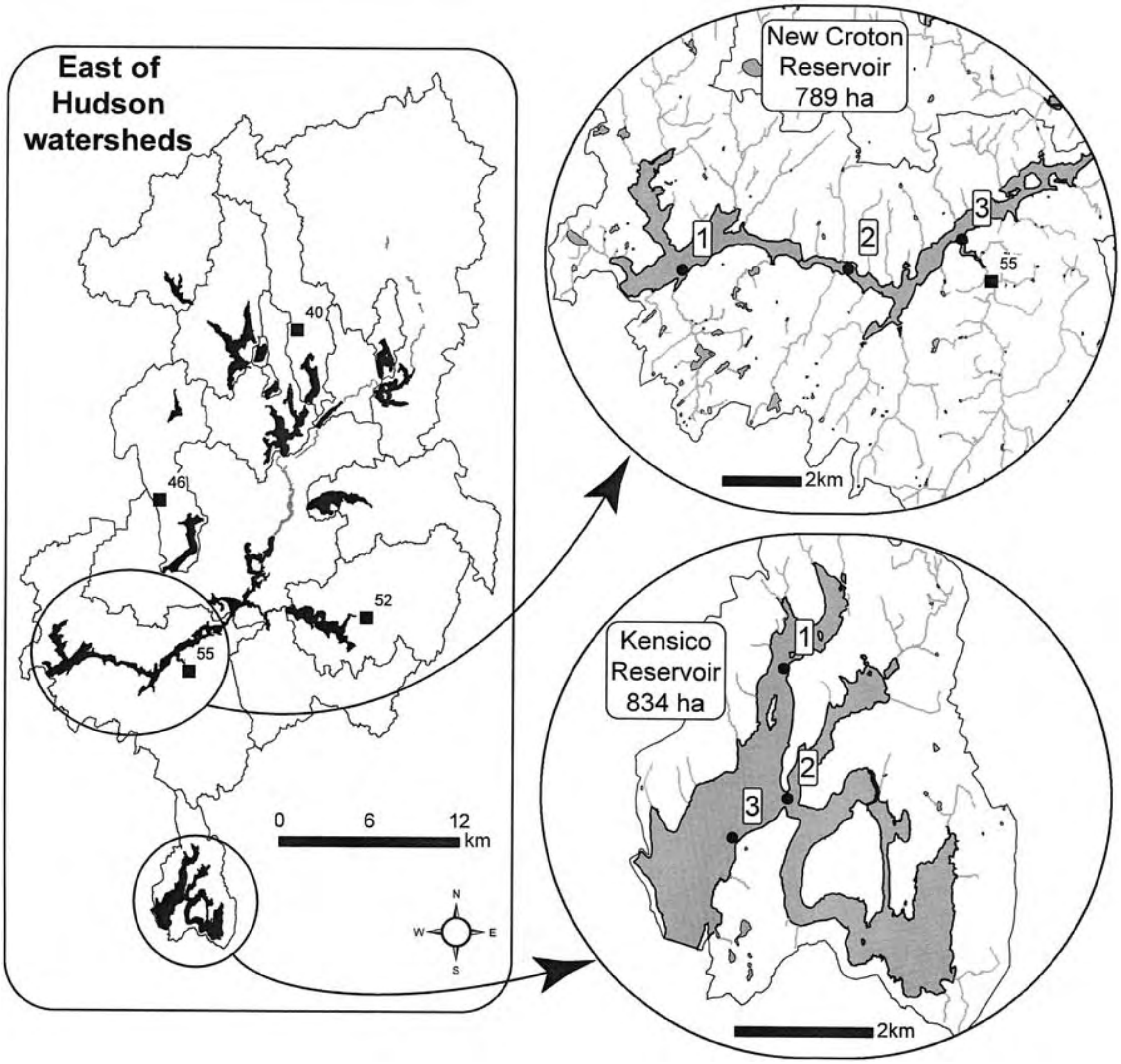

FIG 2. Reservoirs in the east of Hudson River (EOH) watersheds. Reservoir study substations are indicated in each inset and integrative stream sampling sites (Blaine et al. 2006, Bott et al. 2006) are indicated (with site numbers; see figs 1 and 2 in Arscott et al. 2006) on the EOH regional map.

concentrations and algal productivity (Lampert and Sommer 1997). Total daily productivity was estimated by multiplying hourly volume-normalized production rates by 5 h (although some incubations lasted close to 6 h) and then by 1.11 (a factor based on conservative extrapolation of PAR reaching the water surface during the incubation to total daily PAR).

Statistical tests were done on $\log_{10}$(x)-transformed or arcsine$\sqrt{}$(x)-transformed (for percentages) 3-y means. Differences in chlorophyll *a* and light-normalized GPP (GPP/PAR) among reservoirs were determined using ANOVA and Tukey's test (SAS/STAT version 9.0; SAS Institute, Cary, North Carolina). Stepwise multiple linear regression (MLR) was used to identify the influence of local physicochemical variables (e.g., PAR, depth of the photic zone, nutrients, total alkalinity) on chlorophyll *a*, GPP/m^2, and GPP/PAR (Stat-View version 4.02; Abacus Concepts, Berkeley, California). Pearson correlations were used to evaluate relationships among reservoir characteristics and watershed-scale landuse variables (see table 2 of Arscott et al. 2006 and table 2 of Dow et al. 2006). Data for the Kensico in 2000 were excluded from the 3-y mean because of extremely low PAR. Data for Rondout in 2000 were excluded from computation of means because a severe storm and flood in Rondout Creek a few weeks earlier had consequent effects (e.g., high seston load) on the reservoir. Data for Kensico also were deleted from correlation and regression analyses because its water was predominantly of

WOH origin with high turnover, so local land use/cover (hereafter land use) was expected to exert little influence on reservoir characteristics.

Co-inertia Analysis (CIA; Thioulouse et al. 1997; available from: http://pbil.univ-lyon1.fr/ADE-4), an unconstrained, direct gradient multivariate analysis, was used to summarize relationships between watershed-scale land use and in-reservoir productivity, vertical photic and thermal properties, and water chemistry. CIA enables the joint analysis of tables having different numbers of environmental variables, species, or samples (Dolédec and Chessel 1994). All in-reservoir variables (GPP/PAR, GPP/m^2, chlorophyll *a*, photic-zone temperature, photic depth, total dissolved P [TDP], DOC, NH_4-N, and NO_3-N) were $\log_{10}(x)$ transformed and landuse variables were either arcsine$\sqrt{(x)}$ transformed (percentages) or $\log_{10}(x)$ transformed before analysis. Alkalinity was eliminated from these analyses because it was correlated strongly with DOC. Landuse variables were summarized at the watershed level (Arscott et al. 2006), and 3-y means were calculated for SS-specific biological, chemical, and physical data in each reservoir. Thus, data from all SSs within a reservoir were matched with identical landuse variables.

Results

Temperature, O_2, and light penetration

Surface water temperatures ranged from 20 to 25°C and graded to bottom temperatures between 5 and 13°C with a few exceptions (Fig. 3). Bottom temperatures were higher in the Kensico in 2000 (18°) and 2002 (16°) and at SS1 of New Croton in 2002 (18°C). Across reservoirs, the depth of the epilimnion was 1 to 1.5 m in late June to early July and increased to 6 to 9 m in late July to September. The thermocline was not always sharply defined (Fig. 3). For example, in Ashokan, the thermocline was less apparent in mid-September than between late June and early August, and the thermocline usually was poorly developed in both Rondout and Kensico where water residence times were short.

Dissolved O_2 profiles were clinograde (i.e., hypolimnetic O_2 values approached 0) in the Cannonsville (2001) and New Croton (2002) when measured in August, and dissolved O_2 profiles were approaching that condition in July (Fig. 4). Profiles were orthograde (nearly constant O_2 concentration with depth) in the Neversink, Rondout, Schoharie (2002), and Kensico (2001) (Fig. 4). The profiles at some SSs (data not shown for individual SSs) were either positive or negative heterograde (dissolved O_2 concentration elevated or depressed, respectively, at an intermediate depth, usually the thermocline). Positive heterograde profiles occurred in the Pepacton (pronounced at SS2 and SS3 in 2002), Rondout (2002), and Neversink (2002). Negative heterograde profiles occurred in the Schoharie (SS1 in 2001), Kensico (2002), and Pepacton (SS1 in 2001).

SS1 on the Ashokan and Cannonsville were nearest the influent tributaries, Esopus Creek and West Branch Delaware River, respectively. SS3 on the New Croton was near the mouth of the Kisco River. Water depths at these SSs were shallower than at other SSs on those reservoirs (Table 2).

The mean light extinction coefficient (η) was high in the New Croton and Cannonsville and low in the Neversink and Rondout (Table 2). Overall, the depth of the photic zone ranged from ~6 m (New Croton SSs 2 and 3, Ashokan SS1, Cannonsville SS1) to ~10 to 11 m (all SSs on the Neversink, Kensico, and Pepacton) (Table 2). Photic-zone depth increased >2 m in the Ashokan between SS1 and SS3, and ~1 m or more on some of the other reservoirs (Cannonsville, Pepacton, Rondout, Kensico, and New Croton) between the most up-reservoir and most down-reservoir SSs.

Chlorophyll a

Reservoir sampling centered on 5 August (Julian day 217) over the 3-y period. A trend toward higher chlorophyll *a* concentrations in mid- to late-summer was observed when data from each year were combined. When data were expressed as a proportion of the chlorophyll *a* concentration on the earliest measurement date for a particular reservoir, ratios were >1 on all sampling dates after 1 August.

Mean photic-zone chlorophyll *a* concentrations ranged from <10 to ~100 mg/m^2 (Fig. 5A). Chlorophyll *a* concentrations were highest in the Cannonsville, followed by the Kensico and New Croton, and lowest in the Schoharie. The 3 highest-ranking reservoirs had significantly greater concentrations than the 4 lowest-ranking reservoirs; chlorophyll *a* in the Rondout was significantly greater than in the Pepacton and Schoharie; and chlorophyll *a* in the Ashokan was significantly greater than in the Schoharie (ANOVA and Tukey test: $p \leq 0.05$).

MLR analysis of chlorophyll *a* concentrations generated an equation that explained nearly 85% of variance in the data with the inclusion of only GPP (Table 3). Chlorophyll *a* was not significantly correlated with any of the watershed landuse variables, although negative correlations with % coniferous forest ($r = -0.724$, $p = 0.067$), and % mixed forest ($r = -0.727$, $p = 0.065$) were nearly statistically significant.

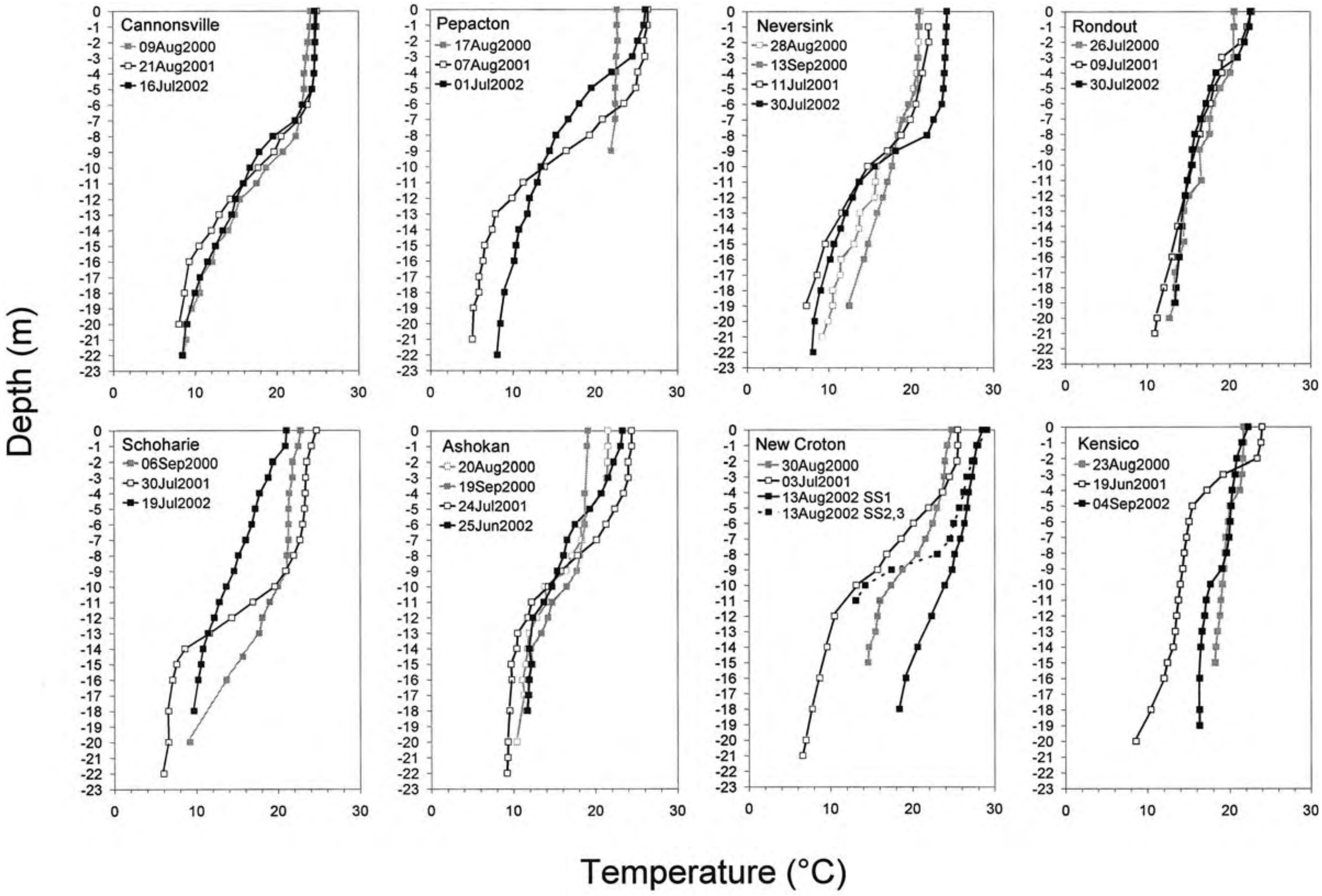

FIG. 3. Temperature profiles (calculated as means across substations [SS] within a reservoir) in each reservoir for each year. Data shown are the means of 3 SSs, except where data from shallow-water SSs (west branch of the Ashokan SS1, Cannonsville SS1 and SS2) were omitted and $n = 1$ or 2. Data were not collected below 9 m on the Pepacton in 2000.

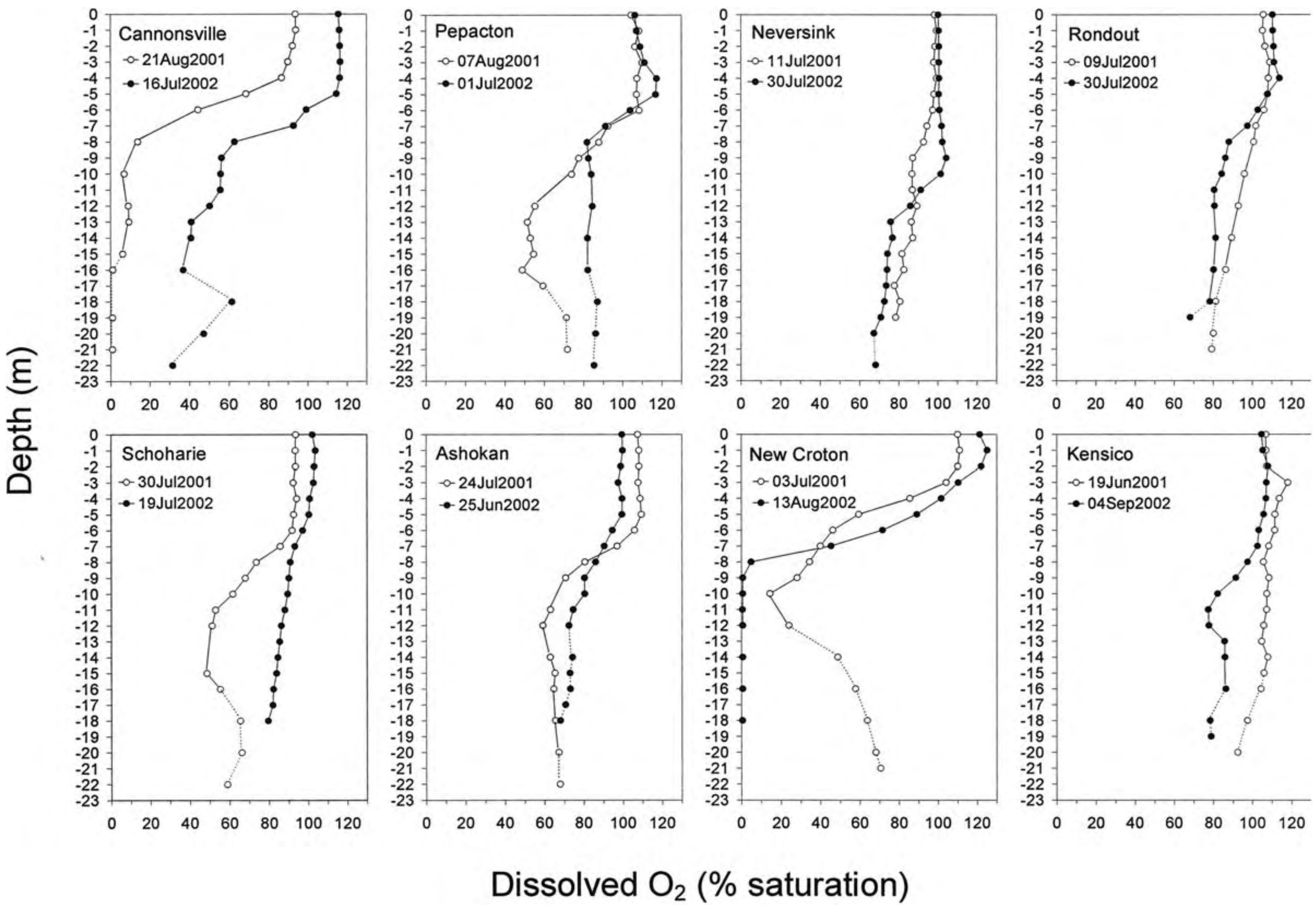

FIG. 4. Dissolved O_2 profiles (shown as mean % saturation) for 2001 and 2002. Data shown are the means of 3 substations (SS), except where data from shallow-water SSs (Ashokan SS1, Cannonsville SS1 and SS2) were unavailable and $n = 1$ or 2 (dashed lines).

TABLE 2. Mean (±1 SD) depths of the water column and the photic zone at each reservoir substation and mean light attenuation coefficients (η) for each reservoir west of Hudson River (WOH) and east of Hudson River (EOH) in New York City's source-water watersheds. Ashokan = west basin of the Ashokan Reservoir.

		Depth (m)		
Reservoir	Substation	Water column	Photic zone	(η)
WOH				
Ashokan	1	10.8 (1.4)	6.0 (2.2)	0.614
	2	20.0 (1.7)	7.4 (1.2)	
	3	20.0 (3.4)	8.6 (1.7)	
Cannonsville	1	12.1 (3.7)	5.9 (1.6)	0.670
	2	14.6 (2.8)	6.8 (2.2)	
	3	21.6 (2.8)	7.3 (2.3)	
Neversink	1	19.2 (0.3)	10.8 (2.6)	0.473
	2	18.8 (0.3)	10.8 (2.8)	
	3	18.3 (4.0)	10.4 (2.5)	
Pepacton	1	18.5 (0.9)	9.7 (2.3)	0.500
	2	16.9 (0.1)	10.1 (2.3)	
	3	22.8 (3.1)	10.6 (2.2)	
Rondout	1	22.0 (1.7)	9.9 (1.6)[a]	0.447[b]
	2	17.0 (1.8)	10.5 (0.4)	
	3	17.6 (0.6)	10.6 (0.9)	
Schoharie	1	23.0 (1.7)	7.7 (1.8)	0.615
	2	17.3 (2.3)	8.3 (1.5)	
	3	14.0 (1.7)	7.6 (0.8)	
EOH				
Kensico	1	12.9 (0.1)	9.4 (1.5)	0.475
	2	14.9 (1.6)	10.5 (0.7)	
	3	19.7 (0.5)	10.4 (0.3)	
New Croton	1	20.0 (1.7)	7.0 (0.9)	0.750
	2	11.7 (0.5)	6.3 (0.4)	
	3	10.3 (0.5)	5.8 (0.4)	

[a] Data for 2000 excluded because of high turbidity from scouring rains a few weeks earlier; photic zone depth = 5 m at all substations

[b] $\eta = 0.941$ in 2000

GPP and GPP/PAR

Hourly mean PAR varied from 3.13 to 5.43 mol quanta/m^2 and temperatures were >20°C at the time photosynthesis measures were made (Table 1). Three-year means for GPP/PAR ranged from 0.03 to 0.13 mg O_2/mol quanta PAR (Fig. 5B). GPP/PAR in the Cannonsville was significantly greater than in the Schoharie, Neversink, Kensico, and Pepacton. The rate for the New Croton was significantly greater than the rate for all of those reservoirs except the Kensico. The rates in the Rondout and Ashokan were significantly greater than the rate in the Schoharie (ANOVA and Tukey's test: $p \leq 0.05$). GPP/PAR peaked in mid-to-late summer, and measurements made after 15 July were usually greater than those made before 15 July in each reservoir. The most pronounced increases occurred in the Kensico, New Croton, and Ashokan. The Cannonsville was sampled over a narrower range of dates, and values were similar among years.

MLR analyses produced equations that explained 99% of the variance in GPP using chlorophyll *a*, temperature, and NO_3^-, and 83% of the variance in GPP/PAR using chlorophyll *a* (Table 3). GPP was significantly positively correlated with % cropland + pasture ($r = 0.769$, $p = 0.042$), % grass + brush ($r = 0.759$, $p = 0.047$), and % industry ($r = 0.769$, $p = 0.042$) land uses, and negatively correlated with % coniferous forest ($r = -0.893$, $p = 0.004$), % mixed forest ($r = -0.802$, $p = 0.027$), % coniferous + mixed forest ($r = -0.896$, $p = 0.004$), and % total forest ($r = -0.859$, $p = 0.010$) land uses. GPP/PAR was significantly negatively correlated with % coniferous forest ($r = -0.788$, $p = 0.033$) and % coniferous + mixed forest ($r = -0.792$, $p = 0.031$) land uses.

Gradients within reservoirs

GPP/PAR at each SS within a reservoir was expressed as a proportion of the GPP/PAR at the SS farthest from the major incoming tributary to that reservoir. An up- to down-reservoir gradient was observed each year in the Cannonsville, with maximum rates occurring at SS1 near the West Branch Delaware River (Fig. 6A). An up- to down-reservoir gradient was observed in the New Croton in 2000 and 2002 but not during 2001 (when measurements were done 1–2 mo earlier than in the other years) (Fig. 6B). A strong up- to down-reservoir gradient was observed in 2002 in the Pepacton, with maximum rates occurring at SS1 near the East Branch Delaware River. This gradient was not observed in 2000, and data for SS2 were suspect in 2001 (Fig. 6C). Up- to down-reservoir gradients were weak in the Ashokan (except for a peak at SS2 in 2000; Fig. 6D) and in the remaining reservoirs.

Up- to down-reservoir gradients of chlorophyll *a* concentrations were observed in the Cannonsville during 2000 and 2002, with maximum concentrations at SS1 (Fig. 6E). In the New Croton, maximum chlorophyll *a* occurred at SS3 near the mouth of the Kisco River in 2002 (Fig. 6F). The maximum occurred at SS2 (farther down-reservoir) in 2000 and 2001, but never at the most down-reservoir station. In the Pepacton, maximum chlorophyll *a* occurred at either SS1 (closest to the East Branch Delaware River) or at SS2 (Fig. 6G). In the Ashokan, chlorophyll *a* concentrations typically increased along the up- to down-reservoir gradient but decreased on 2 August 2000 and showed little change on 25 July 2001 (Fig. 6H). Clear

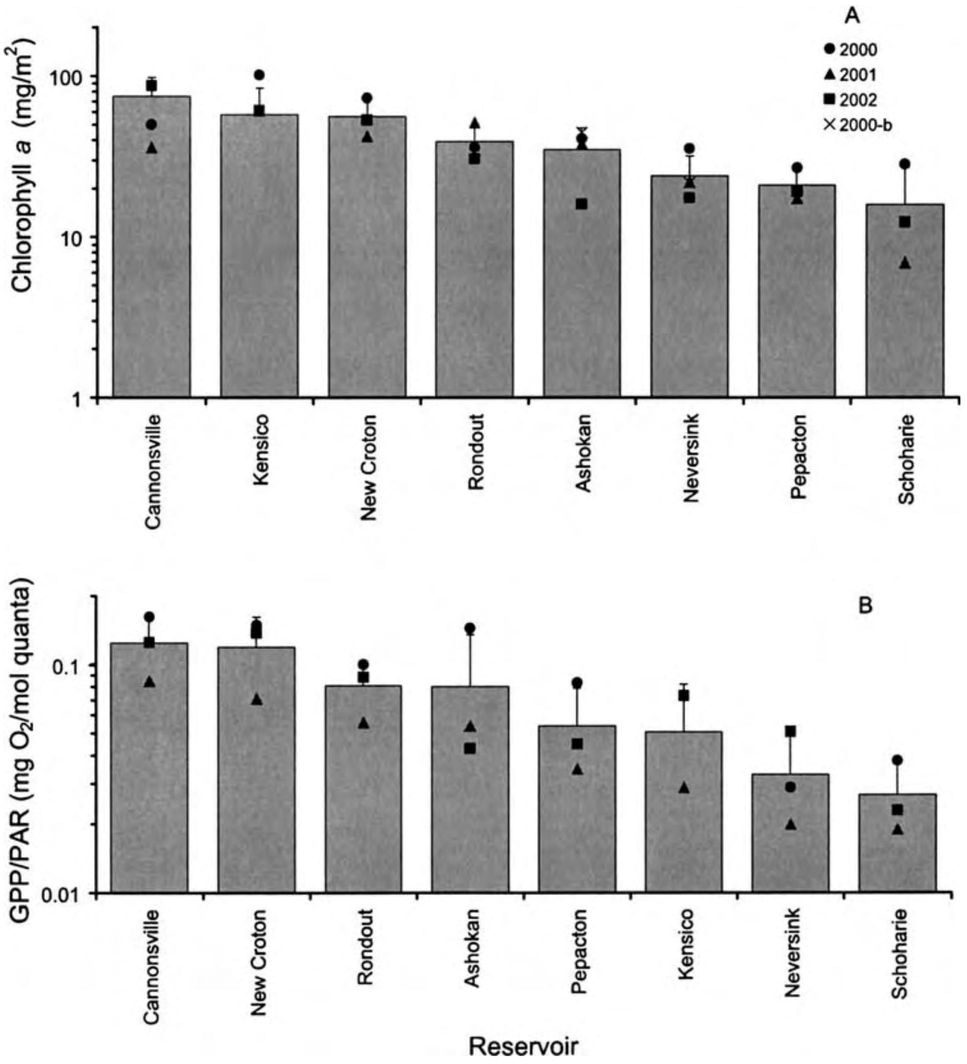

FIG. 5. A.—Ranking of reservoirs based on 3-y mean (+1 SD) chlorophyll *a* concentrations, with data for individual years shown by symbols. B.—Ranking of reservoirs based on 3-y mean (+1 SD) light-normalized gross primary productivity (GPP/PAR), with data for individual years shown by symbols. Data for the Kensico in 2000 were deleted because of extremely low PAR. x = an additional measurement on Neversink in 2000.

gradients in chlorophyll *a* did not occur at other times or in the other reservoirs.

Reservoir–tributary linkages

Three-year mean values for GPP/PAR in a reservoir were plotted against GPP/PAR (adjusted for saturation of photosynthesis as described in Bott et al. 2006) measured at a site on the major tributary to the reservoir or, in the case of the New Croton, at a site on a minor tributary (Kisco River) close to the reservoir (integrative sites, Blaine et al. 2006, Bott et al. 2006). The Cannonsville reservoir with high GPP/PAR was coupled with a site 48 km upstream on the West Branch Delaware River that had moderate GPP/PAR (Fig. 7). The Neversink reservoir with low GPP/PAR was coupled with a site 12 km upstream on the Neversink River that had moderately low GPP/PAR, whereas the Schoharie reservoir with low GPP/PAR was coupled with a site 21 km upstream on Schoharie Creek with high GPP/PAR (Fig. 7). The Ashokan and Rondout reservoirs with intermediate GPP/PAR were coupled with sites 24 km upstream on Esopus Creek and 7 km upstream on Rondout Creek that had moderate and high GPP/PAR, respectively (Fig. 7). The New Croton reservoir with high GPP/PAR was coupled with a site 1.3 km upstream on the Kisco River that had lowest GPP/PAR of the streams used in these comparisons (Fig. 7).

TABLE 3. Multiple linear regression equations for chlorophyll *a* and primary productivity (Kensico excluded) in 7 reservoirs in the New York City source-water watersheds. GPP = gross primary productivity m^{-2} h^{-1}, PAR = photosynthetically active radiation, GPP/PAR = light-normalized primary productivity, temp = temperature, chl*a* = chlorophyll *a*, SRP = soluble reactive P, TDP = total dissolved P, TA = total alkalinity, β = standardized partial regression coefficients (given in order of variables in equation).

Dependent variable	Equation	Variables included in analysis	Adjusted R^2	p
$\log_{10}(\text{chl}a)$	$= 0.885\log_{10}(\text{GPP}) + 2.031$ $\beta = 0.929$	Temp, PAR, depth of photic zone, GPP, GPP/PAR, NH_4-N, NO_3-N, SRP, TDP, TA	0.84	0.0005
$\log_{10}(\text{GPP})$	$= 0.877\log_{10}(\text{chl}a) + 1.808\log_{10}(\text{temp}) - 0.207\log_{10}(NO_3\text{-N}) - 4.595$ $\beta = 0.835, 0.240, -0.238$	Temp, PAR, depth of photic zone, chl*a*, NH_4-N, NO_3-N, SRP, TDP, TA	0.99	0.0003
$\log_{10}(\text{GPP/PAR})$	$= 1.054\log_{10}(\text{chl}a) - 2.793$ $\beta = 0.925$	Temp, depth of photic zone, chl*a*, NH_4-N, NO_3-N, SRP, TDP, TA	0.83	0.0028

Co-inertia analysis

Concordance between watershed-scale landuse and in-reservoir data matrices was highly significant (Monte Carlo permutation test [10,000 times], $p \leq 0.001$). Factor 1 (F1) accounted for 47.1% and 54.7% of the variability in the landuse or in-reservoir data matrices, respectively, and these axes were highly correlated with each other ($r = 0.91$). Factor 2 (F2) accounted for 32.8% and 16.4% of the variability in the landuse and in-reservoir matrices, respectively. However, F2 for the landuse matrix was poorly correlated with F2 for the in-reservoir matrix ($r = 0.69$), and the weak correlation limited our ability to interpret relationships between matrices along F2.

In-reservoir productivity and water-chemistry variables contributing to the definition of the F1 axis (Fig. 8A) were photic-zone temperature (PhoticTemp, 19% of F1 definition), DOC (16%), GPP/m^2 (16%), TDP (13%), and GPP/PAR (10%). Only NH_4-N (57%), DOC (17%), and chlorophyll *a* (10%) contributed substantially to the definition of F2. Landuse variables contributing to the definition of F1 (Fig. 8B) included annual watershed-area-normalized point-source discharges (13%), % other urban (11%), % cropland + pasture (8.6%), % mixed brush-grassland, (8.3%), and % commercial (8.0%). Many landuse variables contributed equally to the definition of the F2 axis including: % farmstead (9.6%), road density (9.4%), population density (9.0%), watershed area (8.9%), and % residential (8.6%).

Three primary patterns emerged from the plot of SSs on F1 and F2 (Fig. 8C). First, the Cannonsville and New Croton SSs clustered along the negative F1 axis, and these SSs had highest primary productivity, photic-zone temperature, chlorophyll *a*, and TDP. Primary land uses in these watersheds were agricultural and rural/urban (Cannonsville) or urban (New Croton). Differences between the Cannonsville and New Croton reservoirs were driven primarily by differences in DOC and NH_4-N concentrations. Second, Kenisco SSs clustered with SSs from WOH reservoirs. Kensico is an EOH reservoir that receives water transfers from WOH reservoirs. Third, SSs closest to contributing streams or reservoirs in the chain (e.g., SS1 in the Cannonsville and SS3 in the New Croton) had the highest primary productivity, chlorophyll *a*, and nutrient concentrations, and these SSs tended to have scores closer to the negative end of F1 than other SSs within a reservoir (i.e., SS scores on F1 decreased in a down-reservoir manner).

Discussion

This survey characterized physical, chemical, and biological conditions in nearly ½ of the reservoirs in the NYC water-supply system during summer. Sampling within each reservoir was limited, but a more in-depth study within the same time frame would have provided coverage of only a few reservoirs. Sampling date can strongly influence results when sampling is limited, but the expected pattern of mid- to late-summer maxima in chlorophyll *a* concentrations and GPP/PAR were observed in several reservoirs when data from different years were combined. In addition, the 3-y mean chlorophyll *a* concentrations in the Cannonsville, New Croton, and Pepacton were within 10% of the means reported by NYC Department of Environmental Protection (NYC DEP) for the entire growing season (May–October 1988–1996; National Research Council 2000). The 3-y mean chlorophyll *a* concentrations in the Rondout and Ashokan were within 30% of the NYC DEP growing-season means, but the 3-y mean chlorophyll *a* concentrations in the Neversink and Schoharie reservoirs were >50% different from the NYC DEP growing-season means. Thus, our data provide reasonable estimates for this important reservoir variable.

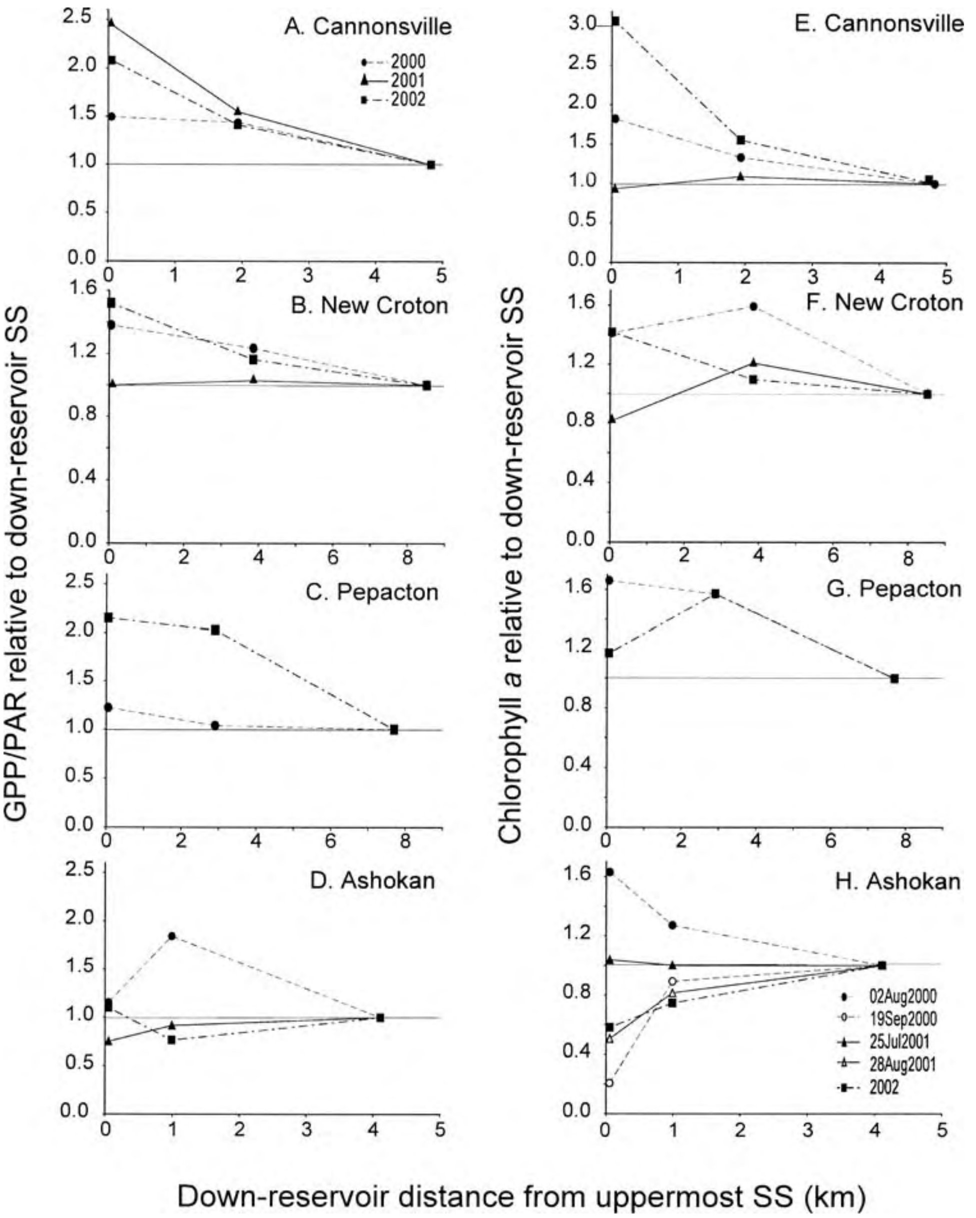

FIG. 6. Longitudinal trends in light-normalized gross primary productivity (GPP/PAR: left column) and chlorophyll *a* concentrations (right column) when data are expressed relative to the respective value at the furthest down-reservoir substation (SS) each year.

Categorization of reservoir condition

Trophic categories have been established for lakes based on chlorophyll *a* concentration and primary productivity. Lakes with chlorophyll *a* concentrations ≤3 µg/L and >10 µg L are categorized as oligotrophic and eutrophic, respectively, with a mesotrophic category between the 2 extremes (Lampert and Sommer 1997). Using these criteria, the Cannonsville reservoir was eutrophic and the New Croton (where the standard deviation for chlorophyll *a* encompassed 10 µg/L) was close to the eutrophic–mesotrophic boundary (Table 4). In contrast, the Schoharie, Pepacton, and Neversink were oligotrophic (although chlorophyll *a* standard deviations in the Neversink and Schoharie overlapped with the boundary for mesotrophic status), and the remaining reservoirs were mesotrophic. Considering individual SSs (data not reported), the 3-y chlorophyll *a* means indicated eutrophic status for Cannonsville SS1 and SS2 and New Croton SS3. These 3 SSs are located toward the head of the reservoir where conditions were influenced by influent water. The standard deviations for Kensico SS2 and Cannons-

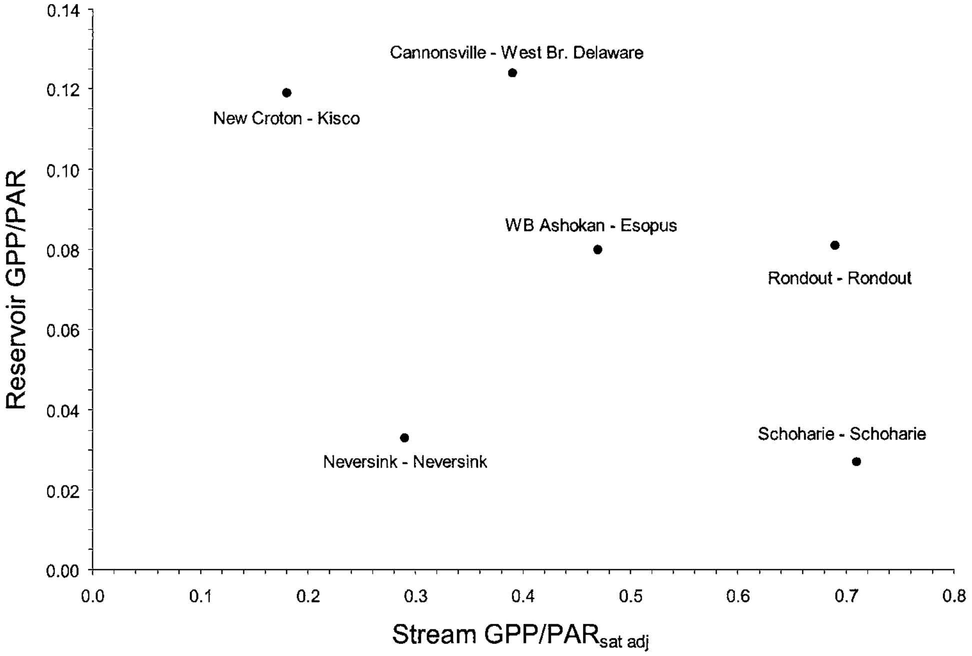

FIG. 7. Relationship between light-normalized gross primary productivity (GPP/PAR) in reservoirs and after adjusting GPP/PAR for saturating light intensities (GPP/PAR$_{\text{sat adj}}$) (both in units of g O_2/mol quanta) at integrative sampling sites (Blaine et al. 2006, Bott et al. 2006) on influent streams.

ville SS3 crossed the mesotrophic–eutrophic boundary. Remaining SSs on the Kensico, and all SSs in the Ashokan and Rondout fell into the mesotrophic category. Means for SSs on the Neversink, Pepacton, and Schoharie were in the oligotrophic category, but standard deviations for many crossed the oligotrophic–mesotrophic boundary.

Oligotrophic and eutrophic lakes are typified by primary productivity values <300 and >1000 mg C m^{-2} d^{-1}, respectively (Lampert and Sommer 1997). These values are approximately equivalent to 0.96 and 3.2 g O_2 m^{-2} d^{-1}, respectively, assuming a photosynthetic quotient of 1.2. Extrapolation of hourly productivity measurements from the 4- to 6-h measurement period used in our study to total daily primary productivity probably yielded underestimates, but our results placed the Cannonsville in the eutrophic category (Table 4). The New Croton was mesotrophic (although nearly eutrophic), as were the Rondout and Kensico, whereas the Pepacton and Ashokan were close to the mesotrophic–oligotrophic boundary. The Schoharie and Neversink were oligotrophic. These results were generally consistent with classification according to chlorophyll *a* concentrations (Table 4).

The chlorophyll *a* concentrations measured in our study were entered into the equation for Trophic State Index (TSI) developed by Carlson (1977). Our TSI values agreed within 10% of the median values reported by NYC DEP (2002) for 1991 to 2000 for all reservoirs but the Neversink, for which the difference was 17% (Table 4).

Other evidence supporting these categorizations comes from dissolved O_2 profiles. The clinograde profiles for the Cannonsville and New Croton reservoirs suggest high rates of photosynthesis in the epilimnion and degradation of accumulated organic matter in the hypolimnion, a pattern characteristic of a eutrophic condition (Lampert and Sommer 1997). In addition, hypolimnetic dissolved O_2 saturation approached 50% at $\geq$1 SSs in the Ashokan, Pepacton, and Schoharie in one of the years of study. Negative heterograde patterns at some SSs in the Pepacton, Ashokan, and New Croton suggest that fine particulate organic matter may have accumulated at the thermocline where it underwent decomposition. Positive heterograde profiles at a few SSs in the Rondout, Pepacton, Ashokan, and Neversink suggest phytoplankton accumulation at the thermocline and elevated primary productivity at that depth. Orthograde (or nearly so) profiles in the other reservoirs suggest a relatively low trophic status.

Temperature profiles for each reservoir displayed expected seasonal patterns, with a deeper epilimnion later in the season and less-pronounced thermocline earlier in the season. We have not examined the influence of water withdrawals on these data, but the Ashokan, Rondout, and Kensico have some of the shorter water residence times among the reservoirs

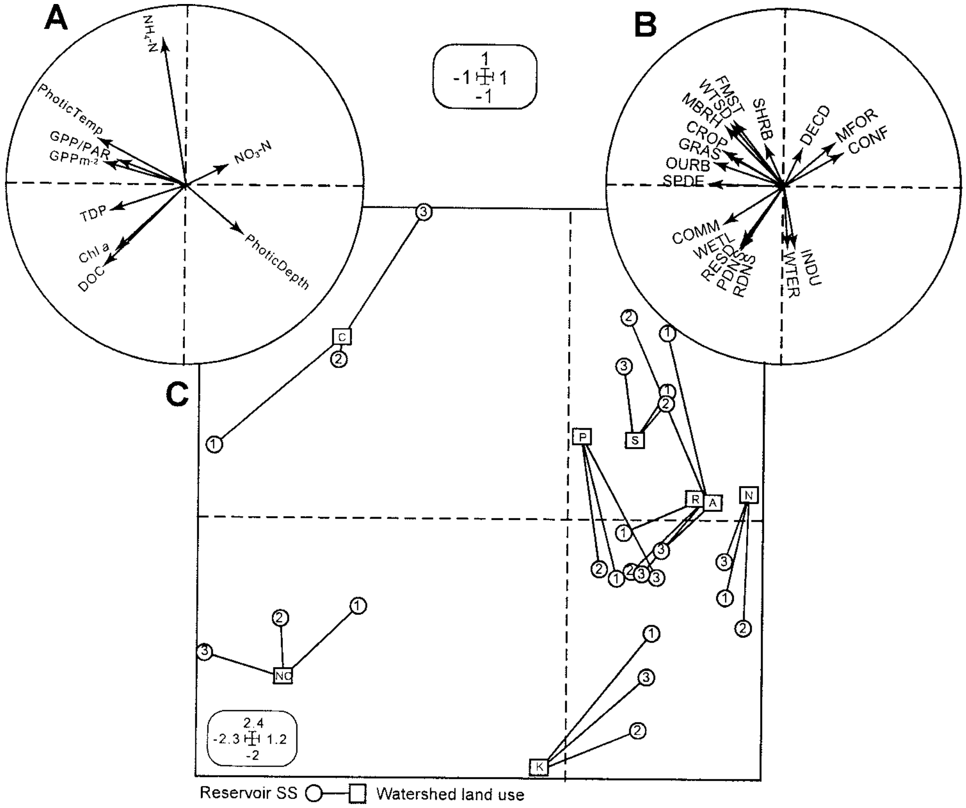

FIG. 8. Co-inertia analysis showing ordinations of in-reservoir productivity, chemistry, and physical variables (A), watershed-scale landuse variables (B), and substations (SS1–3) within each reservoir (C). SSs were plotted based on scores for in-reservoir variables (circles) and reservoirs were plotted based on scores for watershed-scale landuse variables (squares). The lengths of the lines connecting SSs and reservoirs indicate the concordance between the 2 data matrices. Insets show axis lengths. See appendix 2 in Blaine et al. (2006) and table 2 in Dow et al. (2006) for variable names and abbreviations. PhoticDepth = photic depth, PhoticTemp = photic temperature. A = Ashokan, C = Cannonsville, K = Kensico, NC = New Croton, P = Pepacton, R = Rondout, S = Schoharie.

studied (National Research Council 2000) and, thus, less-pronounced thermoclines might be expected in these reservoirs. The Schoharie, which also has a short residence time, had a pronounced thermocline each year. However, unlike the Ashokan, Rondout, and Kensico, the Schoharie is not a transfer reservoir.

Water transparency in many reservoirs was quite good. The large between-year variation in the extinction coefficient for some SSs could be related to numerous factors, including different days and times of day for measurements, changes in reservoir volume related to drawdown and drought, storms that affected turbidity of reservoir water and influent river water, and phytoplankton development. Field observations provided examples of several of these factors: 1) Cannonsville: In 2000, sampling occurred during a bloom of *Microcystis* sp. that was especially pronounced at SS1 near the mouth of the West Branch Delaware River. In 2001, sampling followed an algal bloom observed a few weeks earlier by the field team, and detritus from decay of that bloom might have restricted light penetration. In 2002, the water had a green tint and suspended material was visible at SS1 and SS2. 2) Ashokan: The photic zone at SS1, closest to Esopus Creek, was shallower than at the other 2 mid-reservoir SSs. In 2000, Esopus Creek carried considerable turbidity that apparently influenced the depth of the photic zone at all SSs. In 2001, a brown floc was apparent in some incubation bottles, reflecting a turbidity gradient that was apparent from midreservoir to the mouth of Esopus Creek. 3) Schoharie: Silt was observed at several SSs. 4) New Croton: In 2002, fine suspended material was noted at all SSs, and floating surface material occurred at SS3. 5) Pepacton: In 2002, suspended floc occurred at all SSs, and green floating clumps were noted on the surface at SS1. 6) Neversink and Rondout: In 2002, fine, light green suspended material was observed, even though water clarity was excellent. 7) Kensico: In 2002, all SSs appeared faintly green and visible suspended material was present at SS1.

Particulates from sources other than algal growths affect water transparency in reservoirs. Significant particulate matter is delivered to the reservoirs during

TABLE 4. Reservoir trophic status based on chlorophyll *a* concentrations (Lampert and Sommer 1997), estimated daily productivity (Lampert and Sommer 1997), and Carlson's Trophic State Index (TSI; Carlson 1977). Eu = eutrophic, Meso = mesotrophic, Olig = oligotrophic.

	Chlorophyll *a* (μg/L)		Daily productivity (g O_2 m^{-2} d^{-1})		Carlson TSI[c]		
Reservoir	Mean (±1 SD)	Trophic status	Estimate	Trophic status	1991–2000 median[a]	2000–2002	Trophic status
Cannonsville	12.40 (4.18)	Eu	3.38	Eu	52	53	Eu
New Croton	8.94 (2.89)	Meso–Eu	3.01	Meso–Eu	49	50	Eu
Kensico	5.56 (2.70)	Meso	1.45[b]	Meso	44	45	Meso
Rondout	4.85 (2.21)	Meso	1.47	Meso	42	46	Meso
Ashokan	3.91 (2.32)	Meso	1.17	Meso–Oligo	42	39	Oligo
Neversink	2.48 (1.14)	Meso–Olig	0.88	Oligo	46	38	Oligo
Pepacton	2.26 (0.61)	Oligo	1.30	Meso–Oligo	46	43	Meso
Schoharie	2.00 (1.42)	Meso–Oligo	0.77	Oligo	39	37	Oligo

[a] Data from NYC DEP (2002)

[b] Data for 2000 excluded because of extremely low PAR

[c] Values <40, 40–50, and >50 indicate oligotrophic, mesotrophic, and eutrophic status, respectively

storms, especially following snowmelt (Peng et al. 2004). Some particles delivered in the influent streams settle in the reservoirs, and a sequential reduction of particulate matter has been reported as water passes through the series of reservoirs to the city (National Research Council 2000, Peng et al. 2004). However, resuspension of particles also occurs and can elevate turbidity, and reservoir drawdown increases this source (Peng et al. 2004). Thus, erosion control also has been suggested as one management tool to reduce suspended particulates (Effler and Matthews 2004).

The gradients of photic-zone depth (Table 2), chlorophyll *a*, and GPP/PAR (Fig. 6) document the influence of the major tributary stream on reservoir properties, particularly in the Cannonsville, Pepacton, and Ashokan, which are fed by the West Branch Delaware River, East Branch Delaware River, and Esopus Creek (which also conveys water from the Schoharie reservoir), respectively. Gradients observed in the New Croton may have been influenced by inputs from the Kisco River, which emptied into the reservoir near SS3, but ~80% of the water to the New Croton is delivered from the Muscoot reservoir, which is immediately adjacent in the chain of reservoirs. P loadings to the Cannonsville have exceeded the basin total daily maximum loads (TMDL) in the past (NYC DEP et al. 1999), although the system is currently in compliance (NYS DEC 2004). P loading to the New Croton also exceeded the TMDL limit for that reservoir based on a guidance level concentration of 15 μg/L, but the remaining reservoirs were below watershed-wide TMDL limits. The Cannonsville was a nutrient-saturated system with high productivity in the reservoir and moderately high productivity in its major tributary, whereas the Neversink appeared nutrient limited, with low productivity in both reservoir and river. GPP/PAR was high in Schoharie Creek, as was P uptake velocity (Newbold et al. 2006), presumably retarding the movement of nutrients to the reservoir, which may explain in part why the Schoharie reservoir had lower productivity than the river. Greater turbidity from a high particle load (Peng et al. 2004) and high light extinction also probably reduced productivity in the Schoharie reservoir. Eventually much of the N and nearly all of the P in influent stream water will reach the receiving reservoir where the nutrients may be used immediately by phytoplankton or stored in reservoir sediments. The impact of tributary inputs on reservoir nutrient status is the same in either case, but examination of linkages as done here can help pinpoint where short-term nutrient-control strategies might be most needed and beneficial.

Productivity was greater in the Rondout than in 2 of the reservoirs that deliver water to it, the Neversink and Pepacton. Mixing of water resulting from water transfers may have stimulated productivity in the Rondout, but inputs from Rondout Creek (which ranked moderately high in GPP/PAR among streams) or recycling of nutrients also may have elevated productivity there. Peng et al. (2004) noted that suspended particles decreased as water passed through the sequence of reservoirs for both the Catskill (Schoharie, Ashokan) and Delaware (Pepacton, Neversink, Rondout) chains, whereas silica-containing particles (diatom frustules) were greatest in Rondout. Our finding supports that observation.

Reservoir nutrient concentrations were not well correlated individually with watershed variables, except for DOC and total alkalinity, both of which were positively correlated with landuse variables characteristic of urban watersheds (% residential, % commercial, % industry, population density, road density) and negatively correlated with % mixed forest. Total alkalinity also was positively correlated with State Pollutant Discharge Elimination System (SPDE) discharges (mostly wastewater-treatment-plant effluent) and the number of SPDE dischargers in the watershed. Differences in watershed geology and % wetlands influenced differences between EOH and WOH in alkalinity (Dow et al. 2006) and DOC (Kaplan et al. 2006), and the single EOH reservoir (New Croton) included in these correlations strongly influenced these results. However, multivariate analyses indicated that: 1) reservoir properties were related to land use, 2) the primary reservoir tributary has the strongest influence on those properties in some reservoirs, and 3) within-reservoir processing influences final water quality.

In summary, despite limited within-reservoir sampling, rankings based on chlorophyll *a* and primary productivity indicated a range of reservoir conditions from eutrophic to oligotrophic. In general, trophic-state rankings of reservoirs were in agreement, regardless of which variable (chlorophyll *a* or productivity) was used. Both variables are relevant to the amount of suspended particulate matter in these surface-water supplies. Linkages between reservoir and influent streams were evidenced by gradients of productivity or chlorophyll *a* in some reservoirs, and between ratios of GPP/PAR in streams and receiving reservoirs. Available data concerning nutrient loads to reservoirs generally support these connections. The significant negative correlation of productivity (and nearly significant correlation of chlorophyll *a*) with % forested land use and positive correlations of GPP and GPP/PAR with % cropland and % industrial land use validate ongoing watershed management programs (Blaine et al. 2006) that enhance riparian forest cover and minimize nutrient loading from nonforested landscapes as ways to reduce reservoir productivity and algal biomass.

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