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A Limnological Analysis of Cannonsville Reservoir, NY[1]

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ABSTRACT

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A limnological analysis of Cannonsville Reservoir, NY, is presented that focuses on features related to primary production. Monitoring data collected in 1995, a major drawdown year for the impoundment, and long-term data (since 1974), are evaluated. The reservoir demonstrates eutrophic characteristics in most summers, though upper mesotrophic conditions have been observed in some years. The concentration of chlorophyll is found to be the most reliable indicator of trophic state for the impoundment, as tripton (non-living particulate material) interferes with the measures of Secchi disc transparency and total phosphorus (P) concentration as indicators. Evidence is presented that the sediment resuspension process introduced tripton into the water column in 1995 as the reservoir was drawn down. Oxygen was depleted from the hypolimnion during the summer months of 1995; anoxia prevailed above the deep-water sediments for about 1 month. However, a major release of P from the sediments did not occur during this period. Evidence is presented that nitrogen became limiting to phytoplankton growth in mid-summer, and that a sink process(es) operates for the soluble reactive P released in the hypolimnion from the decomposition of organic material. Longitudinal gradients in trophic state indicators and other features of water quality prevail. Bounds for the riverine, transition, and lacustrine zones are presented; the lacustrine zone represents about 80% of the full reservoir volume.

Key Words: reservoir, impoundment, drawdown, monitoring, eutrophication, trophic state, sediment resuspension, longitudinal gradients, riverine/transition/lacustrine zones.

Reliable tools, in the form of rigorously tested mechanistic mathematical models, are widely desired by lake and reservoir managers to guide management decisions to improve or maintain water quality (e.g., Chapra 1997, Thomann and Mueller 1987). Such models represent a quantitative synthesis of the scientific understanding of processes regulating the concentration(s) of constituents of interest (e.g., nutrients, phytoplankton, oxygen, toxics, etc.). Often it is not recognized that these models can only be as good as the scientific information that supports them. The most reliable models for non-conservative substances are based on detailed limnological and system specific kinetic/process studies, and monitoring of critical forcing (e.g., meteorological, hydrologic, and material loading) conditions. Effective integration of these studies with a modeling program serves to enhance the yield of each and the credibility and utility of the resulting model(s) (see Chapra 1997, Thomann and Mueller 1987).

This issue of the journal documents the findings of integrated interdisciplinary studies that focus primarily on a single flow augmentation/water supply impoundment, Cannonsville Reservoir, New York (NY). Contributions in descriptive limnology, hydrology, hydrodynamics, kinetic and process studies, material loading analysis, and hydrothermal and water quality modeling are presented.

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This manuscript characterizes selected features of the limnology of Cannonsville Reservoir, with particular emphasis on aspects of primary production and related characteristics. The reservoir, its setting, and monitoring programs are described. Historic data are reviewed that depict the system's trophic state and the apparent dependence of related indicator measurements and the character of its stratification regime on reservoir operation. Patterns in time and space are presented and analyzed for a year of particularly intensive monitoring. Important trends, phenomena, and processes are identified from the analysis that have served to guide the design of model frameworks and other studies incorporated in the overall program of study for this system, described in subsequent manuscripts in this issue.

Cannonsville Reservoir

Cannonsville Reservoir (Latitude 42 02' 46", Longitude 75 22' 24", at dam) is located in Delaware County in upstate NY, approximately 190 km from New York City (NYC, Fig. 1). This impoundment is NYC's newest and third largest (of 19) water supply reservoir. Filling of the reservoir began September 30, 1963, after completion of an earth-filled, rock-faced dam downstream from the confluence of the West Branch of the Delaware River (WBDR) and Trout Creek, 2.9 km upstream of Stilesville, NY. The beds of these two streams divide the upper reaches of the impoundment into two arms. The upstream boundary of the WBDR arm of the reservoir is at Beerston, NY (Fig. 1). The reservoir is used primarily as a drinking water supply and to maintain flows in downstream portions of the Delaware River (mandated in a 1954 Supreme Court determination), though recreational fishing is also supported. Cannonsville 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 ~19 m), and a maximum depth near the dam (Fig. 1) of ~49 m. The reservoir has a maximum length of 27.4 km and a shoreline length of about 74 km (Wood 1979).

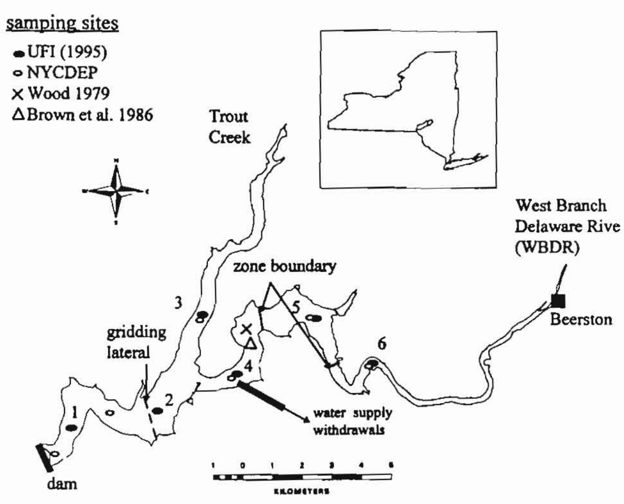

Figure 1.–Cannonsville Reservoir map, with water column sampling locations for intensive 1995 program, sites monitored adjacent to water supply intakes by various programs, position of a lateral transect for three dimensional "gridding," and locations of reservoir within New York State, water supply intakes, dam, approximate bounds of reservoir (e.g., lacustrine) zones and Beerston, NY.

A dimictic stratification regime prevails for Cannonsville Reservoir (Bader 1993, Brown et al. 1986, Wood 1979); e.g., isodensity conditions occur in spring following ice-out and again in fall (spring and fall turnover), strong thermal stratification develops in summer, and weak inverse stratification occurs under ice-cover in winter. The reservoir is a soft water system with limited buffering capacity. The concentration of Ca^{2+} averages about $7.5 mg \cdot L^{-1}$, and alkalinity averages about $16 mg \cdot L^{-1}$ (e.g., NYCDEP 1997).

The annual average completely-mixed flushing rate of Cannonsville Reservoir over the 1969 - 1995 interval was $2.6 y^{1}$ (coefficient of variation (cv) = 18%; Owens et al. 1998b). The interannual variability is attributable primarily to natural, meteorologically-based variations in runoff from the $1,162 km^2$ watershed, and related variations in reservoir operation (Owens et al. 1998b). Substantial interannual and seasonal variations in the water surface elevation (WSE) of Cannonsville Reservoir occur. A detailed treatment of the history of operation and the hydrology of the reservoir is presented by Owens et al. (1998b). Approximately one-third of the annual inflow is received in early spring, associated with snowmelt (Owens et al. 1998b). The WBDR contributes about 80% of the inflow to the reservoir, Trout Creek ~ 5%; the remainder is associated with smaller tributaries and direct inflow (Owens et al. 1998b). Water exits the reservoir in one of three ways: 1) over the dam (spillway) when the reservoir is full (e.g., in spring), 2) via one of three withdrawals (intakes for water supply at depths of 10, 20 and 37 m below the spillway elevation; Fig. 1), and 3) downstream releases (flow augmentation and stream conservation, ~ 35 m below spillway adjacent to dam, Fig. 1). The maximum withdrawal rate for the water supply is $3.0 \times 10^6 m^3 \cdot d^{-1}$, the maximum release rate is $\sim 5.7 \times 10^6 m^3 \cdot d^{-1}$. Flow augmentation requirements for the lower Delaware River can be met by releases from Cannonsville Reservoir or from nearby Pepacton and Neversink Reservoirs (two other NYC impoundments).

The watershed, located in the northwestern section of the Catskill Mountains, has variable topography, with elevations that range from 350 m (at the dam) to 1010 m above sea level; its area is $1160 km^2$ (WBDR sub-basin is 78% of total). It drains in a southwestern direction into the reservoir. The annual average precipitation within the watershed is ~ 100 cm · yr^{-1} [New York City Department of Environmental Protection (NYCDEP) records]. The underlying bedrock is made up of consolidated sandstone, siltstone and shales, covered by gravel, sand, unconsolidated fill and clay (Soren 1963). Most of the agriculture is located along the watershed's stream corridors, where the soils have superior drainage capability. The vegetative cover in the watershed is about 70% forest, 24% grass, and 3% corn or alfalfa. Almost all of the agricultural land is associated with dairy farming. There are about 210 farms, with a total of approximately 20,000 dairy cows (Longabucco and Brown 1990). Approximately 18,000 people resided in the Cannonsville watershed in 1980; 8,400 were served by 5 municipal wastewater treatment facilities (WWTP) (Brown et al. 1986). Two other small WWTPs operate in the watershed to treat waste from agriculture products. The largest WWTP is located in Walton, 7 km upstream of the mouth of WBDR (Fig. 1). NYC owns the land immediately adjacent to the reservoir. Thus the shoreline is protected from development and direct nutrient input from septic systems. Subsequently in this issue, Longabucco and Raferty (1998) review several aspects of external material loading to Cannonsville Reservoir, with particular emphasis on phosphorus.

Monitoring Programs for the Reservoir

The NYCDEP conducts an extensive monitoring program on all 19 of the reservoirs in NYC's water supply system. All outflows and WSE are monitored continuously for Cannonsville Reservoir by NYCDEP (data record reviewed by Owens et al. 1998). Inflow from WBDR (8 km upstream of Beerston, Fig. 1) and flow downstream (2.25 km) of the reservoir are monitored continuously by the United States Geologic Survey. NYCDEP monitors the water quality of WBDR and Trout Creek, outflows from the reservoir, and the water column of the reservoir. The in-reservoir program includes field measurements and chemical and biological laboratory analyses (Table 1) conducted according to standard methods. Instrument profiles are collected at 1-m-depth intervals (NYCDEP 1995). Samples for laboratory analyses are collected at three or four depths for this program, extending from the upper layers to the near bottom, at six longitudinal stations [five along the main axis of the reservoir, one in the Trout Creek branch (Fig. 1)]. Sampling frequency was about monthly over the 1988-1993 interval, but increased to bi-weekly in 1994 (some differences, according to analyte). Temporary additions are made to the routine long-term monitoring program on a "needs" basis, to respond to pertinent short-term (e.g., events) concerns. Findings of this long-term monitoring program are published regularly by NYCDEP (e.g., NYCDEP 1992, 1993).

A more intensive in-reservoir monitoring program was executed in 1995, with the intention of enhancing the resolution of limnological processes and to support the development and testing of mechanistic hydrothermal (see Gelda et al. 1998, Owens 1998b) and nutrient-phytoplankton (see Doerr et al. 1998) models for Cannonsville Reservoir. Salient results of the 1995 program are a primary focus of this paper. Additionally, several process studies were conducted in 1995 to support model development, including: 1) identification and quantification of hydrodynamic processes (Owens 1998a), 2) runoff event-based material loading estimates (Longabucco and Rafferty 1998), 3) optical characterizations (Effler et al. 1998b), 4) quantification of deposition of particulate constituents (Effler and Brooks 1998), 5) characterization of the plankton community, 6) quantification of phytoplankton kinetics (Auer 1998), and 7) determination

Table 1–NYCDEP monitoring program for Cannonsville Reservoir; analytes.

Field Measurements	Chemical/Physical Analysis
temperature	turbidity
pH	color
dissolved oxygen	alkalinity
conductivity	chloride
Secchi disc depth	ammonia
scalar irradiance	nitrate plus nitrite
	total nitrogen
	soluble reactive phosphorus
Biological Analyses	total dissolved phosphorus
fecal coliform	total phosphorus
heterotrophic plate count	dissolved organic carbon
fecal strep	total organic carbon
phytoplankton	suspended solids
zooplankton	volatile suspended solids
	major metals - Ca, Mg, K, Mn, Ni, Al, Fe
	trace metals - Cu, Zn, As, Cr, Hg, Cd, Pb, Se, Ag, Be
	silica
	sulfate
	chlorophyll *a*

of sediment-water chemical exchange rates (Erickson and Auer 1998).

The intensive 1995 monitoring program focused primarily on nutrient-phytoplankton issues (Table 2). The six longitudinal sites (designated as UFI, Fig. 1) adopted were positioned at the locations used for the long-term program. Additionally, a "gridding" of field measurements of temperature, transmissometry [as an indicator of turbidity (T_n); e.g., Kitchen et al. 1982], and fluorescence [as a indicator of chlorophyll (Chl); e.g., Cullen 1982] was conducted with a Seabird Sealogger Profiler (Model SBE 25) on six occasions in early fall of 1994 and the summer of 1995. Readings with the profiler were recorded at a rate of 8 s^{-1}, using an instrument descent rate of about 1.2 $m \cdot s^{-1}$, which produces highly resolved (e.g., nearly continuous) vertical profiles. The gridding included 45 sites, and was intended to identify and characterize a significant three-dimensional structure in the distribution of phytoplankton biomass and T_n in the reservoir. Additionally, the Seabird Sealogger was used to collect profiles of these measures, plus scalar irradiance, and specific conductance, at each of the six longitudinal sites weekly, over the April-October interval. Dissolved oxygen and pH profiles (1- to 2-m-depth resolution; Table 2) were also collected weekly, at site 4 (Fig. 1), at ~ 1000 h. Samples for laboratory analyses (Table 2) were collected at 3-m-depth intervals from the surface to the bottom at sites 1, 4 and 5, and at depths of 0, 3 m, and 1 m above the bottom, at sites 2, 3 and 6 (Fig. 1). Other monitoring programs for the reservoir, from which data are used in the subsequent historic analysis, were described by Wood (1979) and Brown et al. (1986).

Review of Historic Data

Limnological studies of Cannonsville Reservoir have focused on the impoundment's trophic state (e.g., Brown et al. 1986, USEPA 1974, Wood 1979). The most widely used indicators of trophic state are the concentrations of total chlorophyll (Chl) and total phosphorus (TP) in the epilimnion and Secchi disc (SD) transparency (Carlson 1977). High levels of primary productivity (i.e., eutrophy) are commonly manifested as high concentrations of Chl and TP and low SD. Chlorophyll concentration should be considered the primary indicator of these three

Table 2.–Analytes and methods for intensive 1995 monitoring program at Cannonsville Reservoir

Parameters	Description
Field Measurements	
Seabird Sealogger Profiler	
temperature	Sea-Bird Inc.
specific conductance	Sea-Bird Inc.
scaler irradiance	Li-Cor Inc.
transmissometry	Sea Tech Inc.
fluorescence	Sea Tech Inc.
Hydrolab Surveyor 3	
dissolved oxygen	
pH	
Secchi disc depth	12-cm-diameter, black and white quadrant
Laboratory Measurements	
chlorophyll (total, Chl)	Parsons et al. 1984
phosphorus	APHA (1992)
soluble reactive (SRP)	method 4500 P, E
total (TP)	method 4500 P, E
total dissolved (TDP)	method 4500 P, B, E
nitrogen	USEPA 1983
ammonia ($T\text{-}NH_3$)	method 350.1
nitrate plus nitrite (NO_x)	method 353.2
total suspended solids (TSS)	APHA 1992, method 2540D
turbidity (T_n)	APHA 1992, method 2130B