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Resolution of spatial patterns in three reservoirs with rapid profiling instrumentation

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Abstract

Rapid profiling instrumentation is used to resolve spatial patterns of temperature (T), specific conductance (SC), chlorophyll (Chl) and beam attenuation (c_{660}), in three dimensional space for three water supply reservoirs (Pepacton, Rondout and Ashokan) located in New York State, U.S.A. Conspicuous patterns depict the operation of important processes that include the development of deep chlorophyll maxima, the entry of major tributary and tunnel inflows as interflows, and the development of benthic nepheloid layers. SC is demonstrated to be a valuable tracer of the interflow process in these reservoirs. Distinct longitudinal structures are documented for T in spring, SC, Chl and c_{660}, along the major axes of Pepacton, Rondout, and one of the two (separated) basins of Ashokan. Substantial differences are demonstrated to prevail between the two basins of Ashokan; treatment as two basins in series is recommended for modeling purposes. Three-dimensional structures in SC and c_{660}, apparently imparted from interflows, are documented for one of the basins of this impoundment. The needs of mechanistic model frameworks to accommodate the observed spatial patterns and processes are considered.

Introduction

Resolution of vertical patterns of physical and chemical characteristics has been a central theme of limnological studies of stratifying lakes and reservoirs because of the fundamental interplay of these features with system metabolism (e.g. Hutchinson, 1957; Wetzel, 1983). Only very limited vertical resolution was possible in early studies because of the laborious and crude measurement and sampling methods (e.g. Birge & Juday, 1911). Scientific and technological advancements have lead to field instrumentation capable of an array of measurements that can be made rapidly over rather fine vertical scales. Multiple vertical profiles, collected at a number of positions in two dimensional space, can lead to resolution of spatial patterns that may be critical to understanding important system-specific processes and can assist in the identification of related environmental drivers. These capabilities were first applied to ocean systems over very large spatial scales (e.g. Anderson et al., 1989; Read & Pollard, 1992; Muller et al., 1995), but application to inland lentic environs has been limited. Such measurements can be particularly valuable where spatial heterogenity and horizontal gradients are common, such as large lakes (Wetzel, 1983) and many reservoirs (Kennedy et al., 1982; Thornton et al., 1990).

Detailed resolution of spatial patterns, obtained with rapid profiling instrumentation, is documented for three New York reservoirs using several limnological measures. Environmental drivers and mediating limnological processes for the patterns are identified and evaluated. These characteristics are considered within the context of the structure and function of these ecosystems, and the needs of mechanistic model frameworks to appropriately accommodate the documented patterns and related drivers in simulation models.

Study systems and methods

Reservoirs

Spatial patterns were characterized in three reservoirs of the New York City (NYC) water supply system, Pepacton, Rondout and Ashokan (Fig. 1). Pepacton and Rondout are in the Delaware System; Ashokan is in the Catskill System (Fig. 1a). Drinking water withdrawals from these reservoirs reach the NYC area via a system of aqueducts (Fig. 1a). Most of the inflow to both Pepacton and Ashokan is received from a single tributary at the upstream end of the reservoir; East Branch of the Delaware River (EBDR; Fig. 1b) and Esopus Creek (Fig. 1d), respectively. Flows are measured continuously in all the primary tributaries by the United States Geologic Survey. Most (>80%) of the water received by Rondout Reservoir is withdrawn (usually from stratified layers) from the three upstream reservoirs, Cannonsville, Pepacton and Neversink, carried by tunnels or aqueducts (Fig. 1a). Ashokan Reservoir has two distinct basins (west and east) separated by a weir; transport from the west to the east basin is controlled by operations. Nearly all of the tributary flow received by this reservoir enters the west basin (Fig. 1d).

Substantial drawdown of the surface is experienced in most years for Pepacton and Ashokan associated with operations consistent with their intended use (water supply and flow augmentation; e.g. Owens et al., 1998). The study reservoirs encompass a broad range of morphology, operating conditions, and flushing rate (Table 1). The range in trophic state represented by these systems is not large; e.g. all are within the mesotrophic category, based on summer average chlorophyll concentrations (Table 1; Upstate Freshwater Institute, 2000). All the reservoirs experience thermal stratification during summer, though the extent is diminished in Rondout because of the large contributions of cold water received from the upstream reservoirs (Upstate Freshwater Institute, 2000). Substantial interannual variations in features of thermal stratification occur in the other two reservoirs (Upstate Freshwater Institute, 2000), driven primarily by interannual differences in the extent of draw down and secondarily by natural variations in meteorological conditions (e.g. Effler et al., 1986; Owens, 1998c). Soils in the Delaware and Catskill Systems are highly erodable; e.g. large quantities of sediment are mobilized during intervals of high runoff and delivered to certain of the reservoirs (e.g. Bader, 1990; Longabucco and Rafferty, 1998).

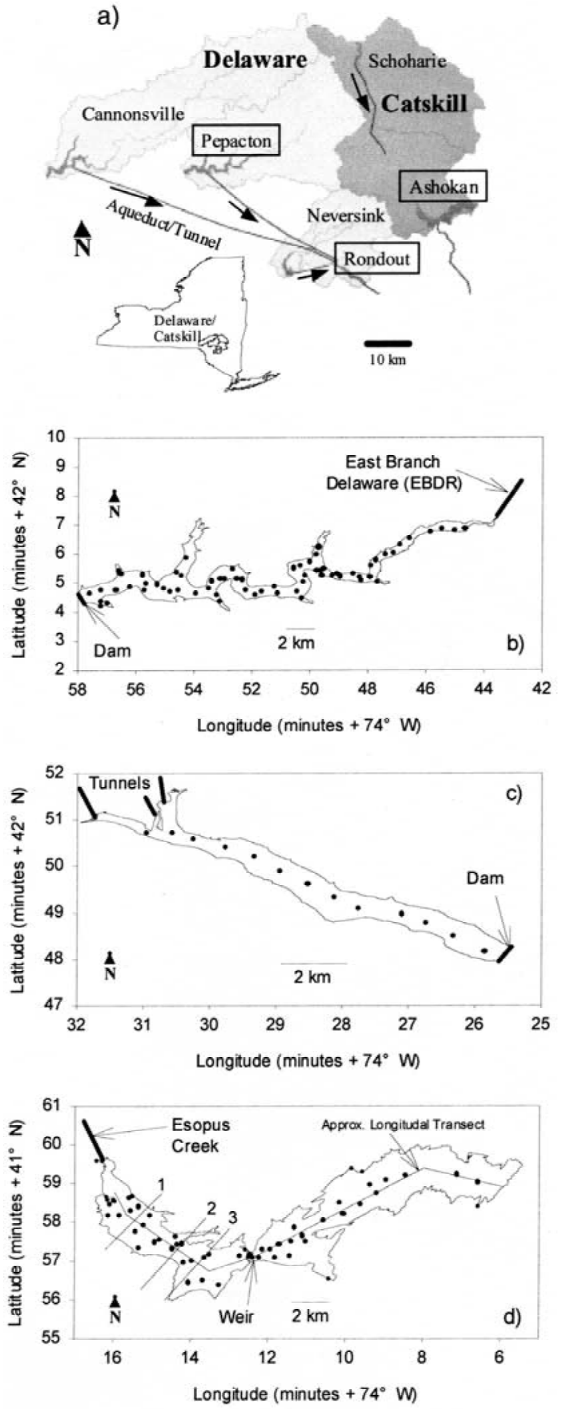

Figure 1. Study reservoirs: (a) positions within Delaware and Catskill watersheds, water supply system, and State of New York, (b) Pepacton Reservoir with vertical profiling positions for 'gridding' of May 22, 1997, and location of the entry of the East Branch of the Delaware River (EBDR), (c) Rondout Reservoir with vertical profiling positions for 'gridding' of May 30, 1997, and (d) Ashokan Reservoir with vertical profiling positions for 'gridding' of June 2, 1997, location of the entry of Esopus Creek, and lateral transects 1, 2, and 3.

Table 1. Characteristics of study reservoirs

Reservoir	Volume[a] ($\times 10^6$ m^3)	Mean[a] Depth (m)	Max.[a] Depth (m)	Drawdown[b] (m)	Flushing[c] Rate (yr^{-1})	Chl (μg l^{-1})
Pepacton	538	27	53	13.9	1.6	3.3
Rondout	200	24	52	10.8	6.8	2.6
Ashokan						
West basin	174	15	47	9.7	5.4	3.9
East basin	299	15	26	8.6	3.1	3.6

[a]Full reservoir values.
[b]Mean of maximum drawdown observed annually; drawdown is the decrease in reservoir elevation relative to a full capacity case.
[c]Mean annual value.

Table 2. Instrument specifications

Instrument	Variable	Manufacturer/ model	Specifications range	Accuracy	Resolution
SeaBird Profiler		CTD SBE-25			
	Depth	SBE-29	0–68 m	±0.2 m	0.01 m
	T	SBE-3F	−5–35 °C	±0.002 °C	0.003 °C
	SC	SBE-4C	0–70 S m^{-1}	±0.003 S m^{-1}	0.0004 S m^{-1}
	Chl	Wetlabs (Sea Tech)	0–100 μg l^{-1}	±30%	0.1 μg l^{-1}
	BAC/c_{660}	Chelsea	0–100 m^{-1}	±0.30 m^{-1}	0.03 m^{-1}
Hydrolab		Data Sonde 3			
	T			±0.15 °C	0.01 °C
	SC			1.5 μS cm^{-1}	0.01 μS cm^{-1}

Instrumentation and field protocols

Paired measurements of depth, temperature (T), specific conductance (SC), chlorophyll (Chl; by fluorescence) and transmissometry were made with an array of sensors configured in a steel cage, and powered by a SeaBird Sealogger Profiler (Table 2). Transmissometry measures the beam attenuation coefficient (BAC) at 660 nm (c_{660}; m^{-1}); thereby accommodating the effects of scattering from all particles plus a prominent absorption peak for phytoplankton (Kirk, 1994). All sensors were calibrated before the field season (e.g. annually), as recommended, by the manufacturer. Eight measurements per second were collected for each variable during profiling and stored in the instrument's data logger. The cage was lowered on a cable at a rate of ~0.5 m s^{-1}; i.e. approximately 16 measurements were made with each probe over each meter of depth. Measurements (n~4) within 0.25 m depth intervals were averaged. The goal was to extend the profiles to within 1–2 m of the bottom of the reservoirs. Some variation in this feature of the profiling was unavoidable, thereby potentially compromising the full resolution of near bottom patterns such as benthic nepheloid layers (BNLs; Link, 1994; Hawley & Murthy, 1995; Effler et al., 1998a). The cage (~35 kg with sensors) was retrieved with a winch.

The profiling at multiple horizontal positions (e.g. a 'grid') conducted on a single day (<6 h for completion) for a reservoir is described as a 'gridding'. The layout of the grids differed somewhat between the reservoirs and between 'griddings' of the same reservoir. However, there were certain unifying features of the design of the grids. The profiling sites extended nearly end-to-end along the primary axes of the reservoirs and were spaced approximately equal distances from each other in each of the basins (Fig. 1b–d). Sites along lateral axes were also approximately equal distances apart, but the spacing was subject to some variation among these transects (Fig. 1d). Usually 30–60 sites were profiled for the 'griddings'. Site locations were established by the Global Positioning System (GPS; accurate to within ~50 m). 'Gridding' was conducted in 1997, a year in which the extent of draw down was described as typical (Upstate Freshwater Institute, 2000); it was performed on 7, 7

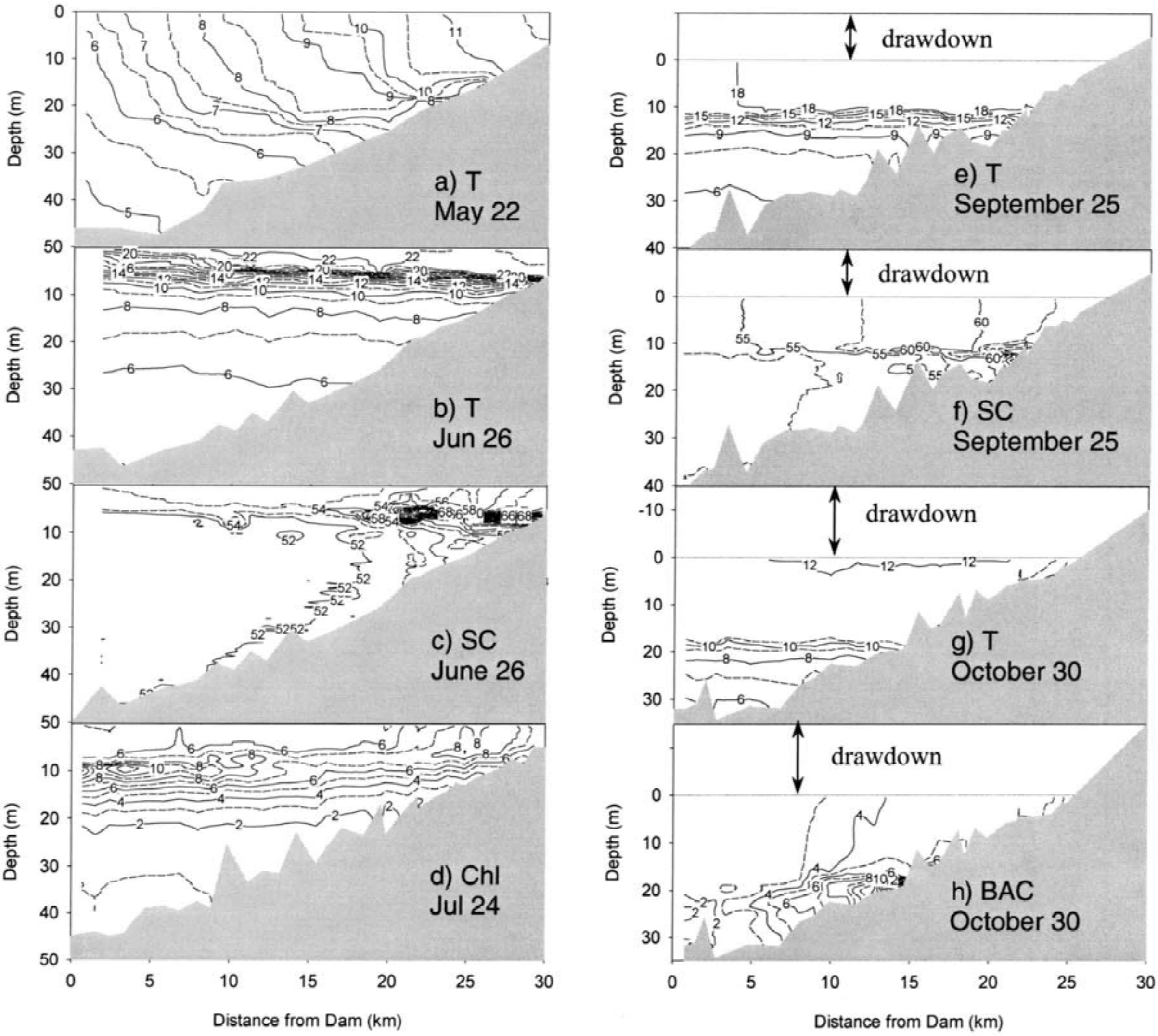

Figure 2. Longitudinal contours along the primary axis of Pepacton Reservoir in 1997: (a) T, May 22, (b) T, June 26, (c) SC, June 26, (d) Chl, July 24, (e) T, September 25, (f) SC, September 25, (g) T, October 30, and (h) BAC, October, 30. Extent of drawdown indicated.

and 12 occasions for Pepacton, Rondout and Ashokan, respectively. Example 'grids', for which results are subsequently presented, are shown for each of the reservoirs (Fig. 1b–d).

The differences in T and SC between EBDR and Pepacton and Esopus Creek and the west basin of Ashokan were documented through measurements with remote sensors (Hydrolab Data Sonde 3; Table 2) in tributary mouths and fixed frequency (weekly) measurements at upstream locations in these basins. Analysis of tributary characteristics responsible for some of the patterns revolved by the 'gridding' were supported by these dynamics.

Results and discussion

Pepacton Reservoir

Longitudinal and vertical patterns of the variables are represented for selected days as contour plots. Longitudinal distance is referenced from the location of the dam, and follows the primary axis of the reservoir (Fig. 1b). Substantial lateral structure was not observed in Pepacton Reservoir. The isotherms of late May in Pepacton Reservoir (Fig. 2a), when the basin was full, depict a distinct longitudinal gradient, reflecting the more rapid heating of the shallower upstream sections adjoining the major tributary (Fig.

1b) as summer stratification was developing. This pattern is attributable to the greater effects of the various heat influxes in this shallower portion of the reservoir, including the primary tributary inflow (relative to downstream portions of the reservoir; Figs 2a and 3a; e.g. Johnson & Merritt, 1979) and exchanges at the air–water interface (e.g. Edinger et al., 1968). This structure is expected to be recurring in spring associated with the seasonality of these heat fluxes; a similar pattern has been documented for nearby Cannonsville Reservoir (Gelda et al., 1998; Owens, 1998a). The temperatures of the primary tributary and the surface water in an adjoining upstream portion of the reservoir were nearly equivalent at the time of this 'gridding' (Fig. 3a), thus this inflow tended to be mixed throughout the upper waters in this interval (e.g. Ford & Johnson, 1983; Alavian et al., 1992; Owens, 1998b).

Thermal stratification was more well established throughout Pepacton Reservoir, and much of the earlier longitudinal structure had been eliminated, by late June, though a deeper and somewhat warmer upper mixed layer prevailed in the upstream portions of the basin at the time of this 'gridding' (Fig. 2b). Distinctly higher SC values were observed within the metalimnion in upstream portions of the basin on the same date (Fig. 2c), depicting the entry of the primary tributary as an 'interflow' (e.g. Ford & Johnson, 1983; Alavian et al., 1992; Owens, 1998b). This entry of an inflow into stratified layers can occur when a tributary is more dense (e.g. colder) than reservoir surface waters; the negatively-buoyant tributary flows down the submerged river channel, entering the water column at a position where its density is equal to that of the water column (Ford & Johnson, 1983; Alavian et al., 1992). The interflow phenomenon is observed in many reservoirs (Thornton et al., 1990), but is rare by comparison in lakes (Wetzel, 1983). The occurrence of the phenomenon in Pepacton Reservoir is supported by coincident T and SC data for the primary tributary (Figs. 3 and 4). Temperatures of this tributary over the mid- to late June interval were distinctly lower than the reservoir surface (Fig. 3a), matching approximately those at the depths of the elevated SC levels (Fig. 2b,c). Specific conductance serves as a valuable tracer of the interflow phenomenon for this reservoir and for other basins in the Delaware and Catskill Systems because the contributing ionic species (mostly Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, HCO_3^{-}, and Cl^{-}; New York City Department of Environmental Protection, 1993) behave in a nearly conservative manner and substantial differences in reservoir surface and inflow values commonly develop seasonally because of the dependence of tributary levels on flow (Fig. 4). Tributary values of SC decreased with increasing flow (Fig. 4); this dilution effect is observed widely (Manczak & Florczyk, 1974; Effler et al., 1996; Effler et al., 1998b). The SC signature imparted by the interflow diminished progressively along the reservoir's primary axis and was largely dissipated approximately 15 km upstream

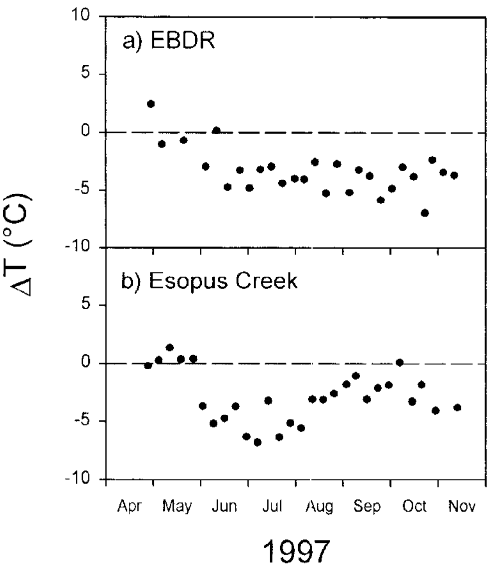

Figure 3. Time-series of differences in T between the primary tributary and surface waters of upstream portions of reservoirs (ΔT=tributary T-reservoir T) for the April–November interval of 1997: (a) East Branch of the Delaware River (EBDR) and Pepacton, and (b) Esopus Creek and Ashokan, west basin.

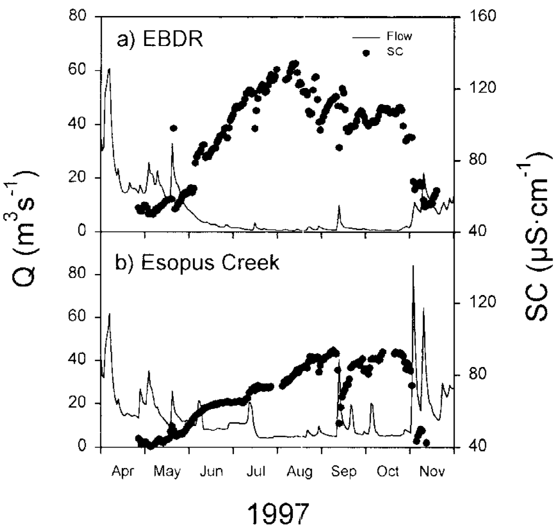

Figure 4. Time-series of tributary flow and SC for the April–November interval of 1997: (a) East Basin of the Delaware River (EBDR), and (b) Esopus Creek.

of the dam (Fig. 2c), presumably in response to the operation of vertical mixing processes (e.g. Jassby & Powell, 1975).

The occurrence of a distinct subsurface (or deep) Chl maximum (DCM; depth ~10 m) over much of the length of the reservoir in late July was clearly depicted by the fluorescence measurements (Fig. 2d). However, the DCM was not uniformly distributed throughout the reservoir. The DCM was more well developed in downstream portions of the reservoir, approaching the dam (Fig. 2d). Vertical patterns of Chl determined by laboratory measurements following extraction of filtered samples (Parsons et al., 1984) were reported to be well correlated to fluorescence profiles in this reservoir on individual days, but the relationship varied between dates (Upstate Freshwater Institute, 2000). The DCM has been reported to occur widely in the stratified layers of oligotrophic and mesotrophic systems, often proximate to the 1% light depth (e.g. Kiefer et al., 1972; Fee, 1976; Brooks & Torke, 1977; Moll & Stoermer, 1982; Coon et al., 1987). A fixed-frequency monitoring program conducted at a lacustrine site in the same year documented the phenomenon persisted more than 5 months over the spring to fall interval in this reservoir (Upstate Freshwater Institute, 2000). Furthermore, the phenomenon is common to other basins in the Delaware and Catskill Systems (Effler & Bader, 1998; Upstate Freshwater Institute, 2000). Evidence has been presented that increases in both phytoplankton biomass and the cellular content of Chl contributed to the DCM in Pepacton Reservoir (Upstate Freshwater Institute, 2000).

The reservoir remained strongly thermally stratified in late September, though the upper mixed layer had deepened and cooled substantially (Fig. 2e) in response to increased kinetic energy inputs experienced seasonally in this region (e.g. Owens, 1998a). The reservoir had been drawn down by more than 10 m at the time of this 'gridding', and features of thermal stratification were essentially uniform along the basin's primary axis (Fig. 2e). The SC signature of an interflow continued to be manifested on this date (Fig. 2f), in response to the lower temperature (Fig. 3a) and higher SC level (Fig. 4a) of the primary tributary relative to the surface waters of the reservoir. The SC signature of the interflow again diminished progressively along the axis of the reservoir (Fig. 2f), in response to the operation of vertical mixing on the interflow signature. The modest decreasing gradient in SC imparted in the upper mixed layer (Fig. 2f) is an outcome of vertical mixing-based inputs from the enriched metalimnion (e.g. Wodka et al., 1983).

The reservoir had been drawdown approximately 15 m (maximum for the year) by the end of October, and the upper mixed layer had deepened to about 17 m (Fig. 2g). The vertical temperature difference for the entire water column for the deepest portions of the reservoir was ~6 °C. The decrease in the temperature gradient within the metalimnion since late September (compare Fig. 2e and g) indicates a reduction in the resistance to vertical mixing, probably driven largely by wind-generated turbulence in the epilimnion (e.g. Jassby & Powell, 1975). Paired contours of BAC depict turbid strata overlying the sediment-water interface in the hypolimnion; e.g. near bottom values of c_{660} were more than four times higher than surface levels in certain areas (Fig. 2h). Such strata are described as benthic nepheloid layers (BNLs), that are usually formed as a result of the operation of sediment resuspension processes (Bloesch, 1995; Hawley & Murthy, 1995). Contributing processes may include sediment focusing (e.g. from sediments in shallow depths; Bloesch, 1995) and resuspension of deep water sediments associated with turbulence (e.g. seiche activity and underflows; Halfman & Johnson, 1989; Gloor et al., 1994). Resuspended sediment can influence the cycling of materials of ecological and water quality significance (e.g. Sigg et al., 1987; Boström et al., 1988), and compromise the interpretation of widely used measures of water quality (Effler et al., 1998a). The BNLs were not uniformly distributed along the reservoir's primary axis (Fig. 2h); rather, the magnitude of c_{660} was generally inversely related to the local thickness of the hypolimnion (Fig. 2g,h). Arguments have been presented that draw down promoted sediment resuspension in Cannonsville Reservoir (Effler et al., 1998a); this may also be the case for Pepacton.

Rondout and Ashokan Reservoirs

Thermal stratification was established in Rondout Reservoir by the time of the late May 'gridding' (Fig. 5a). Profiling sites were limited to the main axis of the reservoir for this 'gridding' (Fig. 1c). The operation of the interflow phenomenon was also clearly manifested in this basin by the pattern in SC imparted on this date (Fig. 5b). The signature of the interflow diminished progressively along the main axis of the impoundment and was essentially eliminated within 2–4 km of the dam (Fig. 5b). However, the interflow(s) entered a broader depth interval in Rondout (Fig. 5b) compared to Pepacton (Fig. 2c, f). At the time of this 'gridding' of Rondout, the basin was receiving withdrawal in-

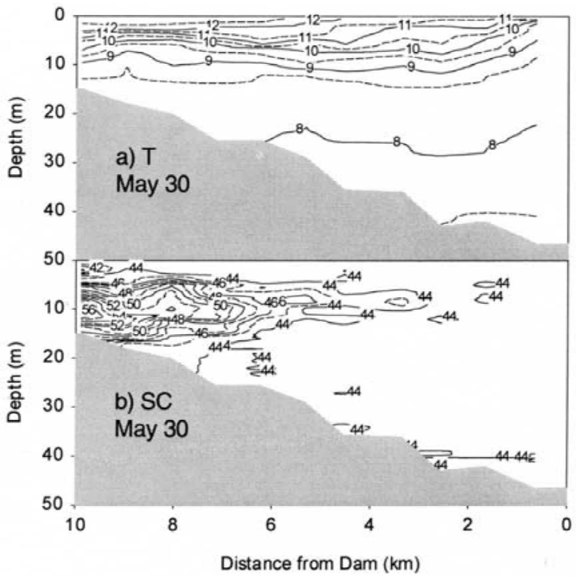

Figure 5. Longitudinal contours along the primary axis of Rondout Reservoir on May 30, 1997: (a) T, and (b) SC.

puts from the hypolimnion of Cannonsville (13.0 m^3 s^{-1}), Pepacton (19.8 m^3 s^{-1}), and Neversink (5.3 m^3 s^{-1}). Levels of SC tend to be higher in Pepacton and Cannonsville, and lower in Neversink, compared to Rondout (e.g. Owens, 1998b; Upstate Freshwater Institute, 2000). The higher SC values observed in the upstream portions of Rondout (Fig. 5b) from the interflows reflect the net enrichment effect of these three inflows. The broader depth interval impacted by the interflow phenomenon in Rondout compared to Pepacton is at least in part due to: (1) the smaller vertical temperature (i.e. density) gradient in Rondout at the time of this 'gridding' (Fig. 2b,e and 5a), (2) the range of temperatures (8–9 °C) of the inflows from the three upstream reservoirs relative to the uniform temperature of the primary tributary for Pepacton, and (3) the high rate and associated turbulence of the inflows entering Rondout.

Longitudinal contours are presented for Ashokan Reservoir for 3 days (Fig. 6) to illustrate patterns imparted by the occurrence of a DCM and interflows, and to contrast these characteristics for the two basins of this impoundment. Thermal stratification was well established for the 'gridding' of early June (Fig. 6a). However, the character of stratification was distinctly different in the two basins; e.g. the metalimnetic gradient was substantially stronger in the east basin (Fig. 6a). Fixed-frequency and -site monitoring (Upstate Freshwater Institute, 2000) and multiple 'griddings' demonstrate substantive differences prevail in the stratification regimes of these basins. A well-developed DCM was observed within the metalimnion of the east basin in early June, though some differences in this vertical pattern were manifested along its longitudinal axis (Fig. 6b). In contrast, the phenomenon was much less clearly resolved in the west basin (Fig. 6b), probably influenced by greater vertical mixing (e.g. Fig. 6a) and reduced light penetration (Upstate Freshwater Institute, 2000) compared to the east basin. These factors are at least in part associated with the west basin's reception of the primary tributary inflow (Fig. 1).

Increased heating of the upper waters had occurred by the late June 'gridding', but the regimes remained different for the two basins; e.g. the metalimnetic gradient in the west basin was distinctly greater on this date (Fig. 6c). The interflow signature of elevated SC in metalimnetic depths was documented along the entire length of the west basin on this date (Fig. 6d). This signature was consistent with the lower temperature (Fig. 3b) and higher SC values (Fig. 4b) of the primary tributary relative to the surface waters of the reservoir in June. This type of pattern was absent in the east basin because it is isolated from this process (Fig. 6d). The longitudinal structure in BAC for the same late June 'gridding' (Fig. 6e) depicts localized effects from the tributary inflow, that has elevated turbidity (mostly clay minerals) relative to the reservoir, even during low flow intervals (Effler et al., 1998b). This signal was imparted as a manifestation of the interflow process. However, it was attenuated more rapidly (i.e. extended over a shorter distance; Fig. 6e), almost certainly because the particles that contributed to BAC behaved less conservatively (e.g. sedimentation) than the constituents of SC. Levels of BAC were lower and more uniform in the east basin (Fig. 6e) associated with lower concentrations of non-phytoplankton particles (Upstate Freshwater Institute, 2000). The general longitudinal structure in BAC was recurring (e.g. Fig. 6f); localization of higher values in the west basin occurred proximate to the primary inflow, tracking features of the interflow, with lower and more uniform values in the east basin.

Though substantive lateral differences were not observed in Rondout, they were observed for SC and BAC in portions of the west basin of Ashokan Reservoir (Fig. 7). These differences were observed repeatedly (e.g. Fig. 7a,b,e,f) in this basin upstream (or west) of the constriction located approximately mid-way along its length (Fig. 1d; e.g. transect 1). A minimum in depth also occurs in this region of the impoundment. These morphometric characterist-

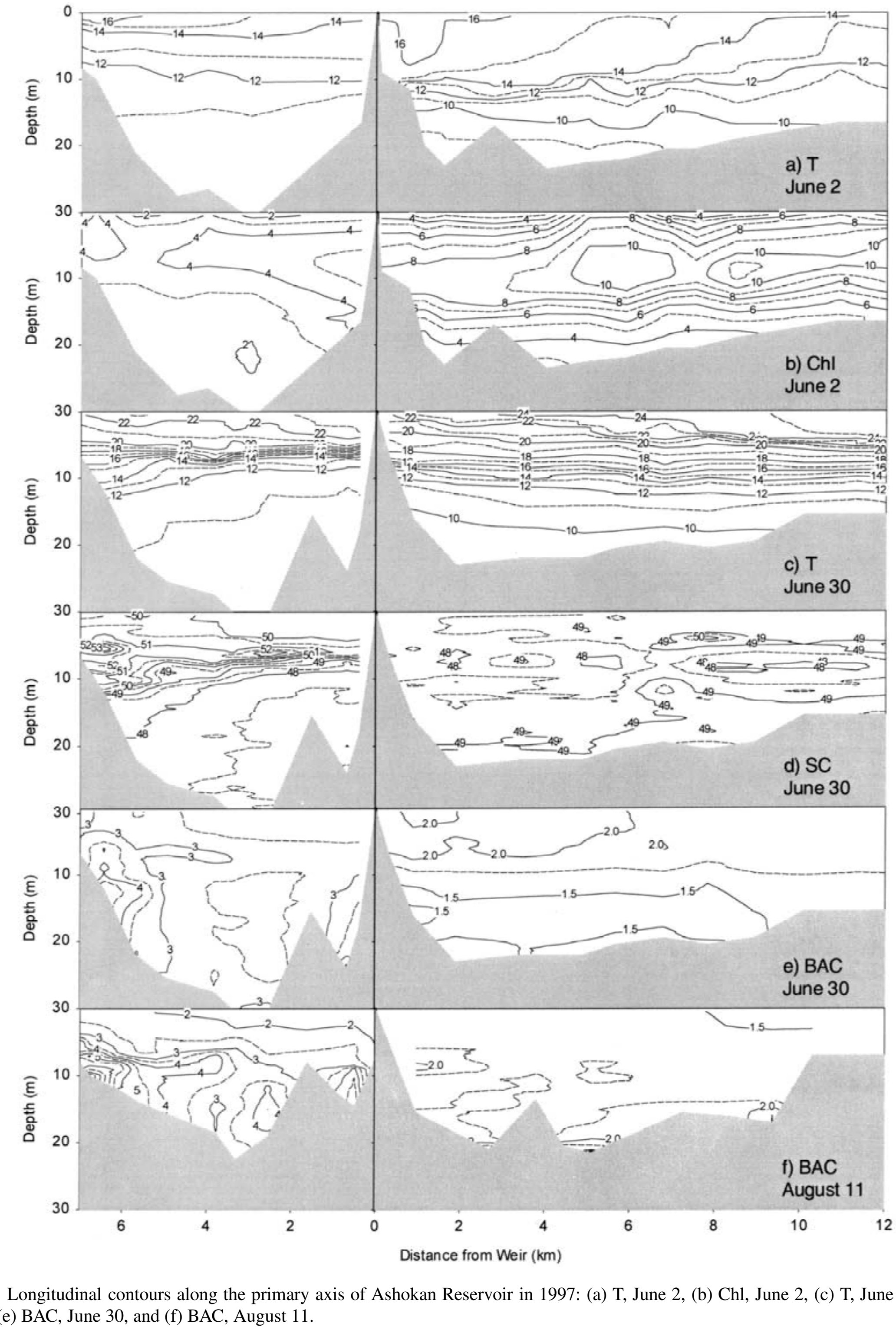

Figure 6. Longitudinal contours along the primary axis of Ashokan Reservoir in 1997: (a) T, June 2, (b) Chl, June 2, (c) T, June 30, (d) SC, June 30, (e) BAC, June 30, and (f) BAC, August 11.

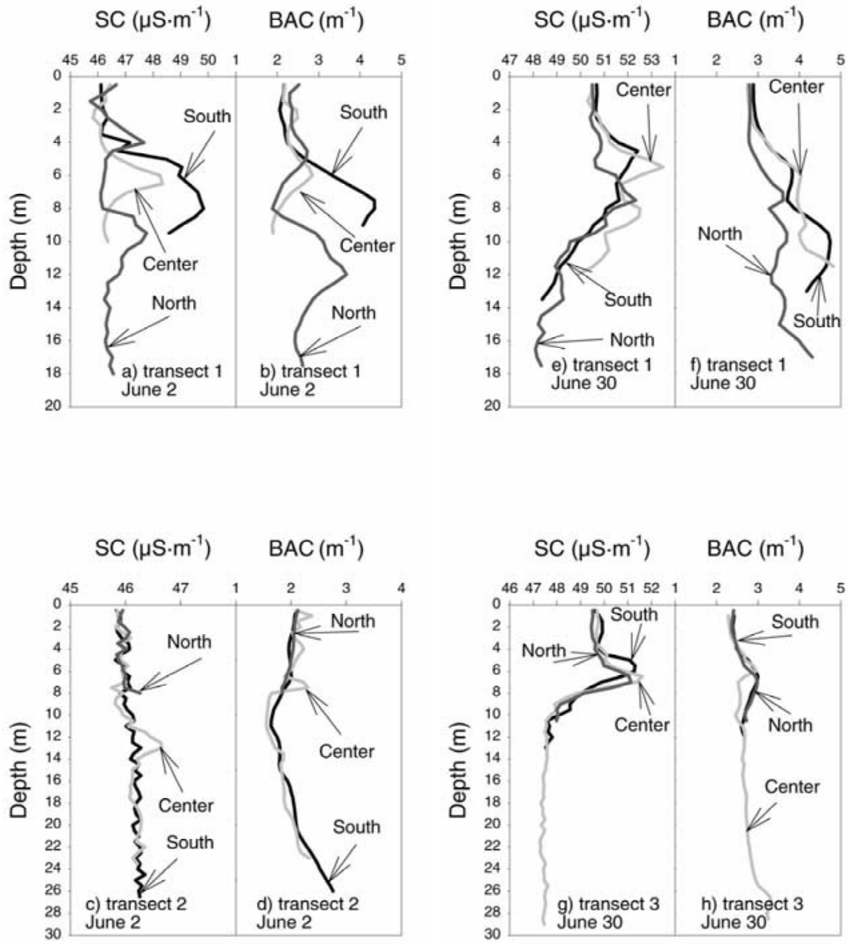

Figure 7. Vertical profiles along selected lateral transects (see Fig. 1d) in Ashokan Reservoir: (a) SC, transect No. 1, June 2, (b) BAC, transect No. 1, June 2, (c) SC, transect No. 2, June 2, (d) BAC, transect No. 2, June 2, (e) SC, transect No. 1, June 30, (f) BAC, transect No. 1, June 30, (g) SC, transect No. 3, June 30, and (h) BAC, transect No. 3, June 30.

ics doubtless impart increased turbulence to inflows as transport proceeds eastward (e.g. Martin & McCutcheon, 1998). In the cases of the early and late June griddings, this three-dimensional character appeared to be driven largely by the irregular nature of the inflow phenomenon in this portion of the basin, as the structure was manifested even in the conservative (e.g. transport) signatures of SC (Fig. 7a,e). While contributions of internal sources of turbidity, particularly sediment resuspension (e.g. Bloesch, 1994, 1995), cannot be discounted, the paired lateral differences in BAC (c_{660}) in this upstream portion of the reservoir (Fig. 7b,f) were qualitatively consistent with the signatures of SC for these 'griddings'. This indicates an important role for external turbidity inputs in regulating these patterns (phytoplankton was not a substantive component of BAC). Vertical structures of BAC in the upper 10–12 m (e.g. epilimnion and hypolimnion) demonstrated a downward vertical displacement from paired SC profiles (Fig. 7a,b,e,f) consistent with settling of externally loaded particles. Nearly uniform patterns of SC and BAC were observed along lateral transects east of the constriction (Fig. 1d; e.g. transects 2 and 3) for both the 'griddings' of early and late June (Fig. 7c,d,g,h), reflecting more complete mixing along this axis in this part of the basin. An attenuated signal of the turbid interflow was manifested in the metalimnion in late June east of the constriction (Fig. 7g,h). We cannot discount the possibility that the three-dimensional signatures imparted to the upstream portion of the western basin of Ashokan would extend throughout this basin after a major runoff event (e.g. Effler et al., 1998b). We attribute the occurrence of three-dimensional characteristics in patterns in upstream portions of this basin, in contrast to Pepacton and Rondout, in part to the broader configuration of the west basin of Ashokan (Fig. 1b–d).

Implications

Spatial structures have been documented here along the vertical, longitudinal and lateral (in the case of the western basin of Ashokan) axes of these reservoirs with rapid profiling instrumentation. Some of the most conspicuous patterns depict the operation of important processes in these basins, including the development of DCM (Figs 2d and 6b), the entry of major tributary and tunnel inflows as interflows (Figs 2c,f, 5b and 6d,f), and the development of BNLs in response to sediment resuspension (Fig. 2h). Distinct longitudinal structures were documented for T in spring (Fig. 2a), SC (Figs 2c,f, 5b and 6d), Chl (Figs 2d and 6b) and BAC (Figs 2h and 6e,f). Ashokan Reservoir represents a special case with respect to spatial structure. Three-dimensional structure was observed over a substantial portion of the west basin of this impoundment under low runoff conditions (Fig. 7a,b,e,f). Furthermore, distinct differences in all the monitored variables prevailed between the two basins of this reservoir (Fig. 6), supporting the treatment of Ashokan as essentially two reservoirs in series (e.g. Upstate Freshwater Institute, 1999). The design of monitoring programs for these and other similar systems need to reflect the character of the spatial patterns to assure representativeness; e.g. specification of horizontal position(s) and depth of sampling.

Longitudinal gradients in features of stratification and measures of water quality are widely observed in reservoirs, associated with the transition from a riverine to a lacustrine environment (e.g. Kennedy et al., 1982; Kimmel & Groeger, 1984; Thornton et al. 1990; Cooke et al., 1993). Kimmel & Groeger (1984) identified three zones, riverine, transition and lacustrine. The longitudinal patterns resolved by the rapid profiling instrumentation represent an objective basis to identify the boundary between the transition and lacustrine zones. We submit that the point of elimination of the interflow SC signature is an appropriate boundary, as this variable represents a conservative tracer received by major tributaries/inflows. Beyond this point, the effects of the inflow have been distributed vertically throughout the water column. Application of this criterion, based on such a conservative tracer, results in a conservative boundary (i.e. minimizes length of reservoir designated as lacustrine); patterns imparted by less conservative materials common to the interflow (e.g. suspended solids/turbidity, as represented by c_{660}) would result in a boundary that would be shifted upstream (e.g. Fig. 6e vs. Fig. 6f). Based on the SC interflow patterns, we would conclude that the lacustrine boundary occurred 10–15 km upstream of the dam in Pepacton Reservoir (Fig. 2e,f), and only a couple of kilometers upstream of the dam in Rondout (Fig. 5b) and the weir in the west basin of Ashokan (Fig. 6d). All of the deep-water areas of the east basin of Ashokan can be considered lacustrine. These observations correspond to the generally low flow conditions encountered over the 'gridding' interval. It is reasonable to expect that the lacustrine zone in these basins would shrink in response to major runoff events.

Mechanistic hydrothermal and water quality models are presently under development for these and other reservoirs in the NYC water supply system, with the goal of using these frameworks as management tools to protect these systems. Hydrothermal models often serve as the physical/transport framework for water quality models (e.g. Thomann & Mueller, 1987; Chapra, 1997; Doerr et al., 1998). The dimensionality of a model, or its ability to make simulations in one- (e.g. vertical), two- (e.g. vertical and longitudinal) or three-dimensional space (e.g. vertical, longitudinal and lateral), is a fundamental feature of model design (e.g. Chapra, 1997). An increase in model dimensionality (e.g. from one- to two-dimensional) represents increased complexity of the physical/transport framework and greater computational requirements. A widely embraced modeling philosophy is the use of the minimum model complexity necessary to credibly accommodate regulating processes and resolve imparted signatures of management significance (e.g. Thomann & Mueller, 1987; Chapra, 1997). This philosophy recommends against a framework with excessive dimensions. Rather, model dimensionality should be selected to match the extent of documented variations in water quality characteristics of interest. If the modeling goals are to simulate reservoir-wide conditions for variables such as Chl and turbidity, the patterns presented here (Figs 2, 5 and 6) support the need for two-dimensional (and perhaps three-dimensional for the western basin of Ashokan for turbidity; Fig. 7) frameworks. However, a simpler one-dimensional framework may be appropriate if modeling goals are limited to the lacustrine zones. Both one- (e.g. Doerr et al., 1998) and two-dimensional (Upstate Freshwater Institute, 1999) models are presently under development for these reservoirs.

The patterns reported here suggest the need to accommodate processes that would represent greater complexity than often encountered in water quality models (e.g. Chapra, 1977). Mechanisms and processes responsible for the development and persistence of DCM have been the subject of debate and are probably to some extent system-specific (e.g. Moll & Stoermer, 1982; Coon et al., 1987). The SC signature imparted by the interflow offers an opportunity to independently estimate the magnitudes of mixing processes (e.g. Martin & McCutcheon, 1998). The proper accommodation of the vertical fate of the interflow may be important for simulation of constituents for which external loading is an important source or driver, as a fraction of this material may be transported downward instead of reaching the upper (e.g. productive) layers. Patterns presented here and other analyses (e.g. Effler et al., 1998a) indicate simulation of the distribution of turbidity in these systems would require proper accommodation of external inputs and the operation of the deposition loss pathway, and, at least in the case of Pepacton (Fig. 2h), the operation of resuspension (e.g. Bloesch, 1994; 1995) as a source.

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