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Characteristics and Origins of Metalimnetic Dissolved Oxygen Minima in a Eutrophic Reservoir[1]

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ABSTRACT

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The occurrence and characteristics of metalimnetic dissolved oxygen (DO) minima are documented, the origins of the phenomena are evaluated, and the contribution of DO consumption in this layer to overall consumption below the epilimnion is resolved, for Cannonsville Reservoir, NY. The analysis utilizes detailed vertical profiles of temperature and DO collected in the lacustrine zone of the reservoir over the 1988-1997 interval, profiles of scalar irradiance and fluorescence measured in 1995, calculations of vertical profiles of phytoplankton production and respiration of DO for selected conditions, and mass balance analyses for DO in the metalimnion and hypolimnion of the reservoir over the 10-year record. The metalimnetic minimum is shown to be a recurring phenomenon in the reservoir, that was conspicuously manifested in late summer in each of the 10 years. The position of the minimum below the water surface has been rather uniform in mid-summer but other features, including the extent of DO depletion, have varied greatly. Respiration of relatively high concentrations of phytoplankton biomass within the metalimnion, located below the compensation depth, contributed to the development of the observed minima. The high phytoplankton concentrations of the metalimnion probably are associated with slowed descent rather than interflow(s). On average, ~ 70% of the DO consumption exerted below the epilimnion over the 1988-1997 interval occurred in the metalimnion. The average DO consumption rate in this layer, normalized for layer volume, was 80 $mg \cdot m^{-3} \cdot d^{-1}$. It was necessary to accommodate the important effects of export and exchanges between layers (entrainment flows) associated with reservoir operations in the mass balance framework used to estimate consumption rate(s).

Key Words: metalimnion, dissolved oxygen, metalimnetic minimum, negative heterograde curve, mass balance, reservoir operation.

The occurrence of a metalimnetic minimum in dissolved oxygen (DO) profiles, alternately described as a negative heterograde curve, is an atypical distribution in lakes (Cole 1994, Hutchinson 1957, Wetzel 1983), though it has been described as common for deep reservoirs (Cole and Hannan 1990, Walker 1987). Cole and Hannan (1990) listed 25 reservoirs where metalimnetic oxygen minima have been observed. A substantial fraction of the total mass of oxygen depleted below the epilimnion in lakes and reservoirs that

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experience the phenomenon can occur within the metalimnion (Wetzel 1983). A metalimnetic minimum may influence certain potential resource uses, and can confound application of widely applied paradigms between trophic state and hypolimnetic oxygen depletion (Mortimer 1941, Walker 1979, Welch and Perkins 1979).

The negative heterograde distribution can have several causes. Respiration/decay of settling seston (e.g., phytoplankton) slowed in descent upon encountering the colder waters of the metalimnion is one cause (Birge and Juday 1911, Drury and Gearheart 1975, Gordon and Skelton 1977, Mitchell and Burns 1979). Metalimnetic minima have also been attributed to respiration of dense populations of non-migrating zooplankton (Shapiro 1960), morphometric irregularities within stratified layers (Hutchinson 1957, Shapiro 1960), and entry of interflows with elevated oxygen demand or depleted DO levels (Cole and Hannan 1990, LaBounty and Horn 1997, Martin 1988, Nix 1981). More than one process may contribute to the occurrence of this vertical distribution in certain systems (Shaprio 1960, Wetzel 1983).

This paper documents the occurrence, describes the characteristics, and evaluates the origins of the metalimnetic DO minimum in Cannonsville Reservoir, NY. The contribution of oxygen depletion within the metalimnion of the reservoir to overall depletion below the epilimnion is documented for a 10-year period that includes a wide range of reservoir operation and drawdown. The analysis relies on the results of detailed vertical profiling for DO and other parameters, measurements of reservoir outflows, calculations of phytoplankton production and respiration of DO for selected conditions, and mass balance analyses for DO in the reservoir's metalimnion and hypolimnion.

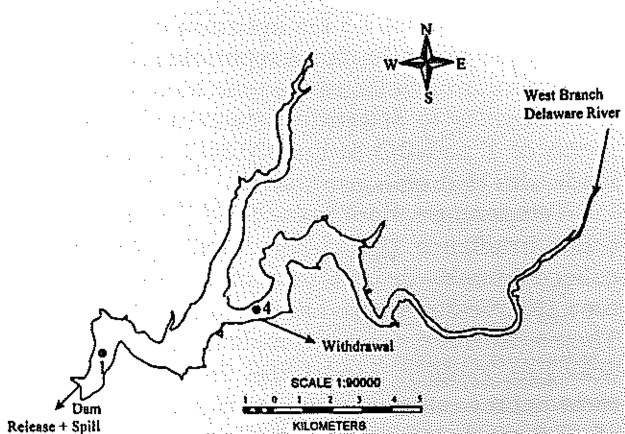

Figure 1.–Cannonsville Reservoir map, with T and DO monitoring sites and locations of water supply intakes and dam.

Methods

System

Cannonsville Reservoir (latitude 42 02" 46", longitude 75 22' 24", at dam) is a eutrophic flow augmentation and water supply reservoir for New York City (NYC), located about 190 km northwest of the City. The West Branch of the Delaware River (WBDR) is the primary tributary (Fig. 1), representing about 80% of the inflow received by the reservoir (Owens et al. 1998). Water exits the reservoir by three routes: "spill" over the dam, release from deep layers at the dam to meet downstream flow requirements, and water supply withdrawals from one of three intakes (10, 20, and 37 m below the spillway elevation) from a mid-reservoir location (Fig. 1). The middle intake is almost always the one used when withdrawals are made. Measurements of all of these outflows are made routinely by the New York City Department of Environmental Protection (NYCDEP). Substantial drawdown of the reservoir has been experienced in many years (Owens et al. 1998).

Detailed descriptions of the reservoir's morphometry, hydrology, and operation (Owens et al. 1998), limnology (Effler and Bader 1998), nutrient loading (Longabucco and Rafferty 1998), optical regime (Effler et al. 1998), oxygen demand of bottom sediments (Erickson and Auer 1998) and hydrothermal and transport characteristics (Owens 1998a, b) have been presented in previous manuscripts in this issue. Doerr et al. (1998) developed and successfully tested a mass balance nutrient-phytoplankton (eutrophication) model for the lacustrine zone of the reservoir. Thermal stratification is rather uniform within the lacustrine portion of the reservoir from late spring through summer (Gelda et al. 1998).

Profiling

Various monitoring programs conducted for the reservoir have been reviewed by Effler and Bader (1998). NYCDEP maintains a long-term monitoring program for Cannonsville Reservoir as part of a larger program that includes all 19 of the City's reservoirs. Detailed profiling of temperature (T, °C) and DO is conducted by NYCDEP in Cannonsville Reservoir at two lacustrine sites. NYCDEP data included in this analysis are those collected over the 1988-1997 interval at these sites, one is located near the drinking water intake (site 4), the other near the dam (site 1, Fig. 1). The lacustrine zone of the primary arm of the reservoir extends from about 1.5 km upstream of site 4 to the dam. The site near the dam is representative of a much larger portion of the lacustrine zone. Monitoring varied from monthly to bi-weekly measurements. Measurements of T and DO in the NYCDEP program were made with Hydrolab instruments.

Temperature, fluorescence (Sea Tech Inc.) and, scalar irradiance (E_s; Li-Cor 193SB) profiles were collected weekly in 1995, at approximately the same time DO measurements were made (~ 1000 hours). These sensors were powered simultaneously by a Seabird Sealogger Profiler (Model SBE 25). Readings were recorded at a rate of 8 s^{-1}, at a instrument descent rate of ~ 1.2 $m \cdot s^{-1}$. Attenuation coefficients (K_s, m^{-1}) were determined from the E_s profiles in 1995 (Effler et al. 1998). Values of K_s were used to calculate (according to Beer's Law) the lower boundary of the (eu) photic zone ($z_{0.01}$; depth at which E_s is reduced to 1% of the subsurface value), that is generally assumed to demarcate the vertical range of photosynthesis for most phytoplankton (Cole 1994, Kirk 1994). Review of similar data from earlier years indicates the conditions documented for 1995 (Effler et al. 1998) were consistent with those that prevailed in other years of the study period.

Calculations of Production and Respiration of DO by Phytoplankton

Photosynthetic production and respiratory loss of DO as a function of depth in the water column of the reservoir were estimated for the documented conditions of August 1, 1995, using expressions incorporated into the nutrient-phytoplankton model for the reservoir (Doerr et al. 1998). Inputs specified for the calculations corresponded to measurements; these included concentrations of nutrients (soluble reactive phosphorus, ammonia and nitrate nitrogen), the daily average incident irradiance, the attenuation coefficient for scalar irradiance (K_s = 0.95m^{-1}; Effler et al. 1998), vertical distributions of chlorophyll (Chl) and T, and related coefficients that quantify the dependence of phytoplankton growth and respiration on these environmental conditions (Doerr et al. 1998). The vertical profiles of Chl and T for this day are presented subsequently with the calculated profiles of photosynthetic production and respiratory consumption for reference. The Chl profile is an estimate generated from the fluorescence profile for that day, by multiplying florescence units by three. The depth profile of vertical mixing presented subsequently for the same day is a simulation from the tested one-dimensional hydrothermal model for the reservoir (Owens 1998c), that serves as the transport framework for the nutrient-phytoplankton model (Doerr et al. 1998).

Oxygen Deficit and Mass Balance Calculations

Apparent oxygen depletion below the epilimnion is represented here as a DO deficit; the observed DO content subtracted from the saturation content for a specified T. Review of spring-time T profiles (values near the bottom soon after the onset of stratification; e.g., Owens 1998a) supports 5 °C for specification of the initial DO saturation content of the reservoir. This representation of initial DO concentrations for the reservoir is further supported by near-saturation DO concentrations observed during early spring in the reservoir (e.g., Effler and Bader 1998).

Estimates of the "apparent" mass oxygen deficit (DOD') were made from the DO profiles and hypsographic information (Owens et al. 1998) according to

$$DOD' = \sum_{i}^{n}[([DO]_{s,5} - [DO]_o)_i \cdot V_i] \qquad (1)$$

where $[DO]_{s,5}$ = saturation concentration of DO at 5 °C, $[DO]_o$ = observed concentration of DO, $([DO]_{s,5} - [DO]_o)_i$ = DO concentration deficit in reservoir layer i, and V_i = volume of layer i. The reservoir was partitioned into horizontal slices of 1 m thickness for these calculations. Calculations of DOD' were made based on the DO profiles collected at site 1, because this site is representative of the majority of the lacustrine zone of the reservoir (e.g., Doerr et al. 1998). Contributions of depletion of DO within the metalimnion versus the hypolimnion to the overall DOD' observed below the epilimnion were resolved, based on demarcations of the layer boundaries assigned from analysis of temperature profiles (Wetzel 1983, Wetzel and Likens 1991).

The value of DOD' is a valid representation of the actual deficit in lakes over intervals of unchanging dimensions of the stratified layers. However, if changes in these dimensions occur over periods of DO depletion then the effects of transport of DO into and/or out of these layers associated with these changes needs to be accommodated. Changes in volumes can be represented as "entrainment flows" from one layer to the next (Doerr et al. 1996). Reservoir drawdown causes changes in layer dimensions greater than encountered in lakes.

Analysis of DO deficit for reservoirs such as Cannonsville Reservoir is further complicated by routine operations that result in export from stratified layers. Water supply and dam release outflows from this reservoir represent exports of oxygen and oxygen deficit from the depleted (Effler and Bader 1998) stratified layers. Exports of oxygen were calculated at a daily time step as the product of the volume of the outflow and the DO concentration at the depth of export. Based on proximity (Fig. 1), in-reservoir measurements of DO at site 4 supported export estimates for the water supply withdrawal and site 1 observations were used to estimate export via dam releases. Dam releases were always from the hypolimnion during summer stratification (Owens 1998a). Water supply withdrawals were either from the metalimnion or hypolimnion depending on the extent of drawdown and the seasonality of the thermal stratification regime (Owens 1998a, c, Gelda et al. 1998).

Assuming that inflows enter only the epilimnion, the water balance equations for the metalimnion and hypolimnion can be written as:

$$\Delta V_M = \Delta t\,(Q_{HM} - Q_{ME} - Q_{OM}) \quad (2)$$

$$\Delta V_H = \Delta t\,(-Q_{HM} - Q_{OH}) \quad (3)$$

where ΔV_M and ΔV_H = changes in the volumes (m^3) of the metalimnion and hypolimnion over an interval of calculation, Δt (d); Q_{HM} = entrainment flow from the hypolimnion into metalimnion ($m^3 \cdot d^{-1}$); Q_{ME} = entrainment flow from the metalimnion into the epilimnion ($m^3 \cdot d^{-1}$); Q_{OM} = export from the metalimnion through a withdrawal ($m^3 \cdot d^{-1}$); Q_{OH} = export from the hypolimnion through withdrawal and/or dam release ($m^3 \cdot d^{-1}$). Assuming that small-scale vertical diffusion is negligible compared to entrainment flows, DO mass balance equations for the two layers can be written as follows:

$$\frac{\Delta(V_M C_M)}{\Delta t} = [Q_{HM} \cdot \alpha \cdot (C_H + C_M) - Q_{ME} \cdot \alpha \cdot (C_M + C_E)] - [Q_{OM} C_M] + S_M \quad (4)$$

$$\frac{\Delta(V_H C_H)}{\Delta t} = [-Q_{HM} \cdot \alpha \cdot (C_H + C_M)] - [Q_{OH} C_H] + S_H \quad (5)$$

where C_M and C_H = volume-weighted average concentrations ($g \cdot m^{-3}$) of DO in the metalimnion and hypolimnion, respectively; S_M and S_H = net consumption rates of DO ($g \cdot d^{-1}$) in the metalimnion and hypolimnion, respectively; and α = a dimensionless weighting factor associated with the DO concentration of entrained waters (between 0 and 1). In the present analysis $\alpha = 0.5$ was used (Doerr et al. 1996). The left hand sides of Eqs. (4) and (5) represent the apparent depletion rates of DO. The three terms on the right hand sides of these equations represent DO changes due to entrainment, outflows, and net consumption, respectively. Using measured outflows (Q_{OM} and Q_{OH}) and observed changes in the volumes of metalimnion and hypolimnion, entrainment flows can be estimated from Eqs. (2) and (3). Equations (4) and (5) can then be used to estimate S_M and S_H. Only sink processes contribute to the values of S_x because of limited light penetration. The magnitudes of S_x are indicative of

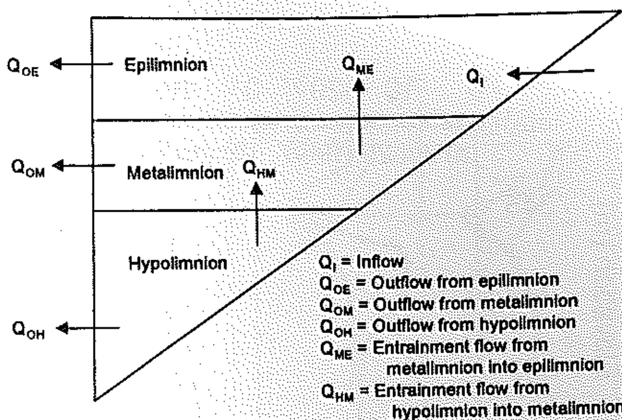

Figure 2.–Conceptual diagram for transport processes for mass balance calculations to determine oxygen consumption rates in the metalimnion and hypolimnion.

metabolic activity. These calculations were made for the intervals between successive depth profiles over the May to mid-August period for each of the 10 years.

Results and Discussion

Recurrence and Characteristics of Metalimnetic DO Minima

Paired T and DO profiles collected in July from site 1 over the 1988-1997 interval (Fig. 3) establish that the metalimnetic DO minimum has been a recurring phenomenon in Cannonsville Reservoir. This period encompasses a rather wide range of drawdown before the July observations, largely in response to interannual variations in runoff (Owens et al. 1998). The position of the minimum at this time of year relative to the water surface has been rather uniform (Fig. 3), the coefficient of variation (CV) for the average (8.9 m) was only 6%. However, other features of the vertical structure of DO within the metalimnetic depression, such as minimum value and shape, have differed substantially over the 10-year period.

Additional features of the phenomenon emerge from the review of profiles collected seasonally. The dynamics of 1996 (Fig. 4) are particularly noteworthy, as the reservoir remained nearly full throughout the spring-fall interval, conditions common to most lakes. Several seasonality features of the metalimnetic DO minimum phenomenon are recurring, including: 1) the timing of its onset, 2) progressive DO depletion through mid-summer, and 3) sensitivity of the vertical structure of the depletion to dynamics in the dimensions of the UML (e.g., Figs. 4 and 5). However, DO

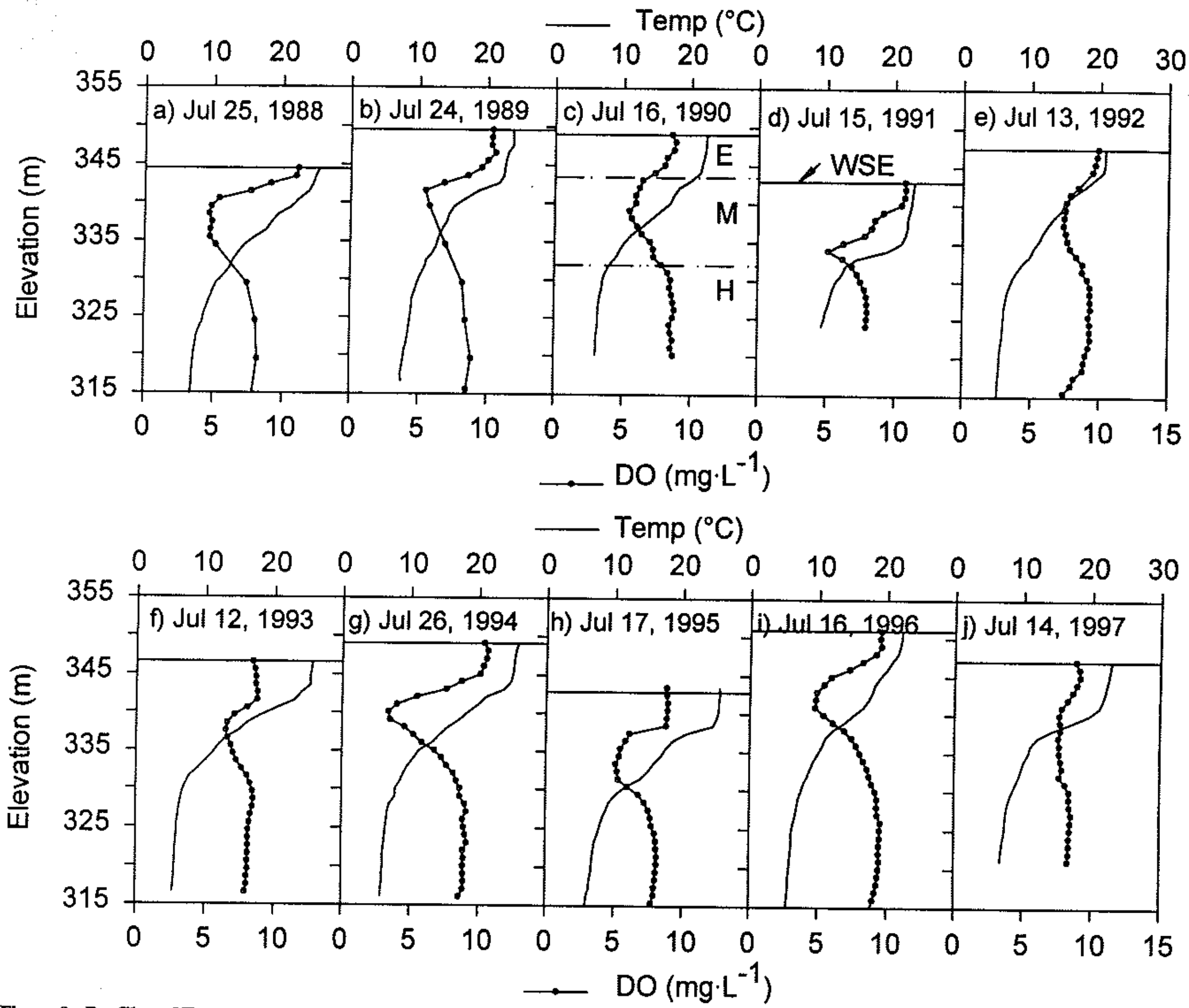

Figure 3.–Profiles of T and DO at site 1 for a day in July for 10 years, over the 1988-1997 interval: a) July 25, 1988, b) July 24, 1989, c) July 16, 1990, d) July 15, 1991, e) July 13, 1992, f) July 12, 1993, g) July 26, 1994, h) July 17, 1995, i) July 16, 1996, and j) July 14, 1997. Protocol for identification of layer boundaries (E - epilimnion, M - metalimnion, H - hypolimnion) shown in c), and water surface elevation (WSE) shown in d).

concentrations remained higher within the metalimnion in 1995 (Fig. 5), a major drawdown year (Owens et al. 1998), than in 1996 (Fig. 4). The minimum was lost earlier in 1995 (late summer) because of the earlier onset of fall turnover associated with the greater drawdown (Gelda et al. 1998, Owens 1998c). Vertical profiles of DOD' below the epilimnion for 1996 (Fig. 6) reflect the effects of both the vertical patterns of oxygen depletion (Figs. 3-5) and layer volumes [e.g., see Fig. 2 of Owens et al. (1998)]. The metalimnetic component of DOD' was greater than the hypolimnetic deficit through summer (Fig. 6), associated with the depleted oxygen concentrations and the larger volumes of the layers within the metalimnion (Owens et al. 1998). The magnitude of DOD' decreased in early fall due to entrainment of the stratified and depleted layers within the deepening epilimnion that accompanied the approach to fall turnover. This is a recurring pattern. This influx of deficit to the epilimnion apparently was largely responsible for the distinctly undersaturated concentrations observed within this upper layer in early fall (e.g., 4j-l). For example, the loss of metalimnetic deficit from September 10 to September 23 due to entrainment can account for about 70% of the undersaturation observed on the later date.

Concentrations of DO decreased in the hypolimnion in late summer with the approach to the sediment-water interface (Figs. 4 and 5). This widely observed pattern (e.g., Cole 1994, Wetzel 1983) is a manifestation of the localization of oxygen demanding processes at this interface and limited vertical mixing. Substantially greater depletion of DO in the hypolimnion at site 4

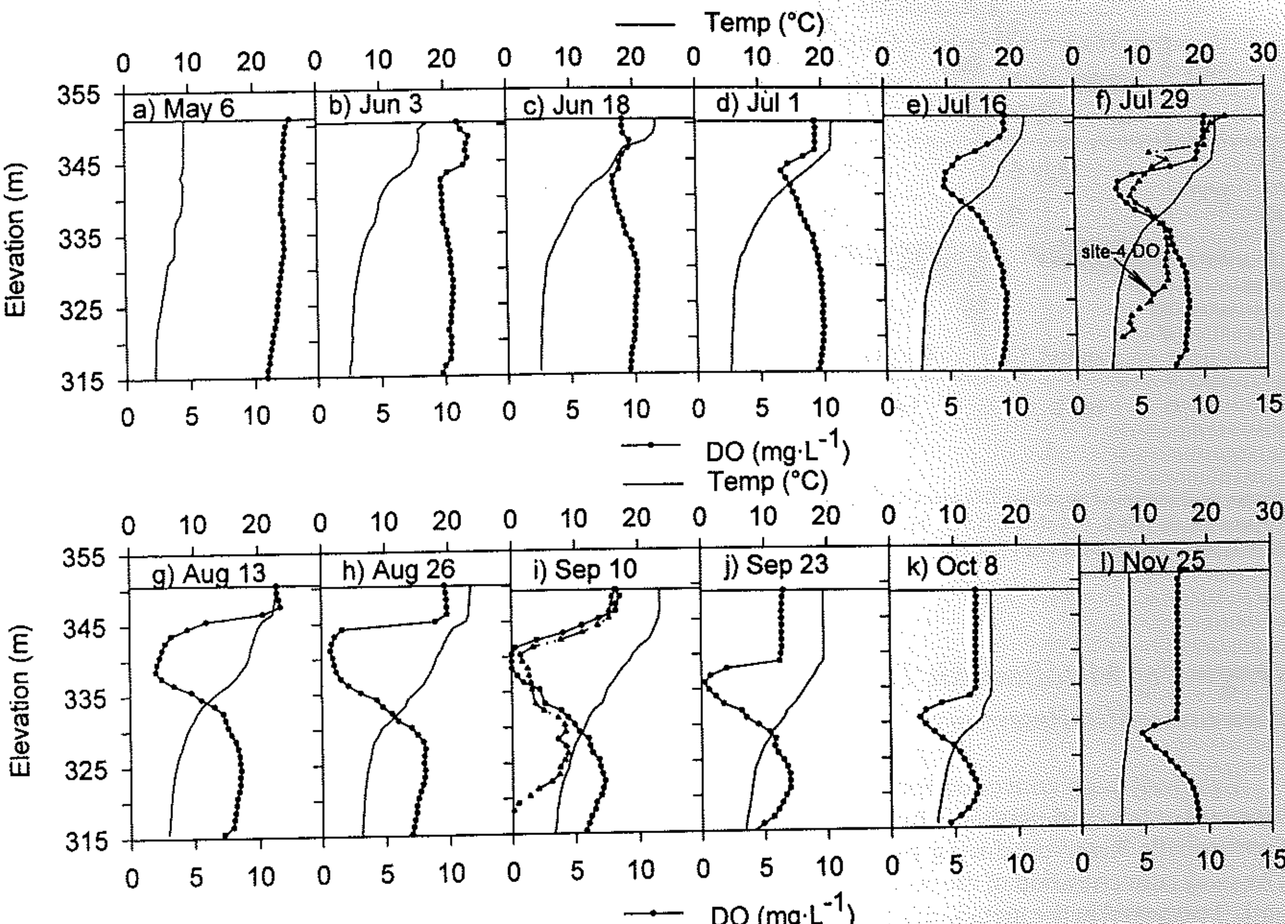

Figure 4.–Profiles of T and DO at site 1 for 12 days in 1996: a) May 6, b) June 3, c) June 18, d) July 1, e) July 16, f) July 29, g) August 13, h) August 26, i) September 10, j) September 23, k) October 8, and l) November 25. Profiles of DO at site 4 included in f) and i).

compared to site 1 (Fig. 4f and i) is attributable to the smaller volume of the overlying hypolimnetic water relative to the interface area with the sediments in the upstream portion (including site 4) of the lacustrine zone. Pronounced differences in hypolimnetic DO concentrations between these sites reflect limited longitudinal exchange in these deep layers within the lacustrine zone of the reservoir.

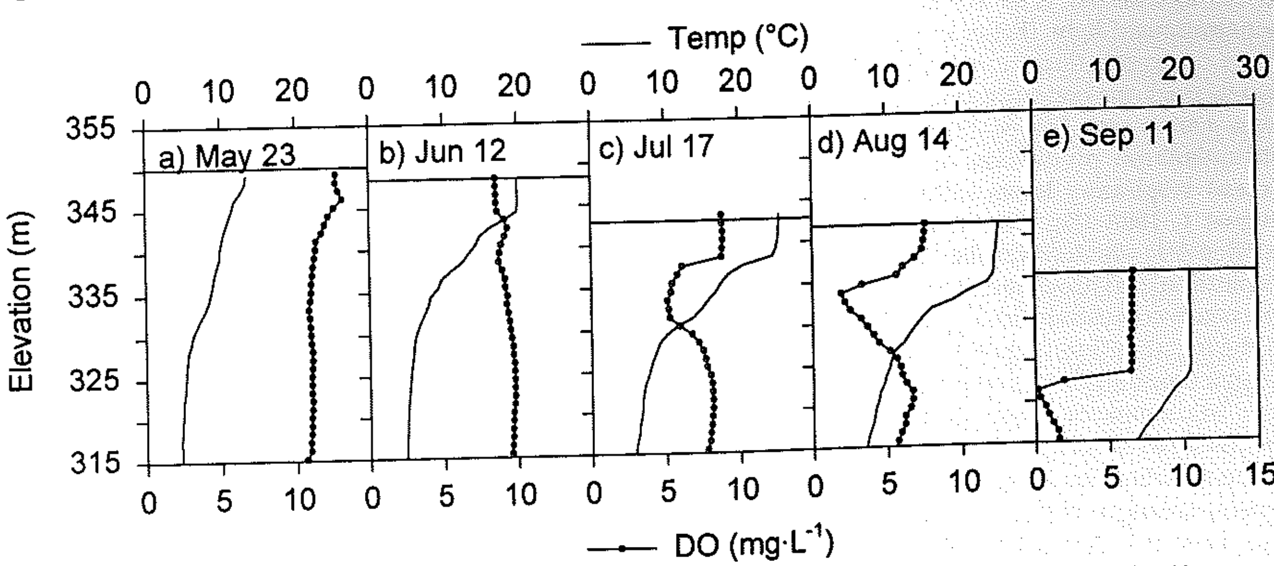

Figure 5.–Profiles of T and DO at site 1 for 6 days in 1995: a) May 23, b) June 12, c) July 17, d) August 14, and e) September 11.

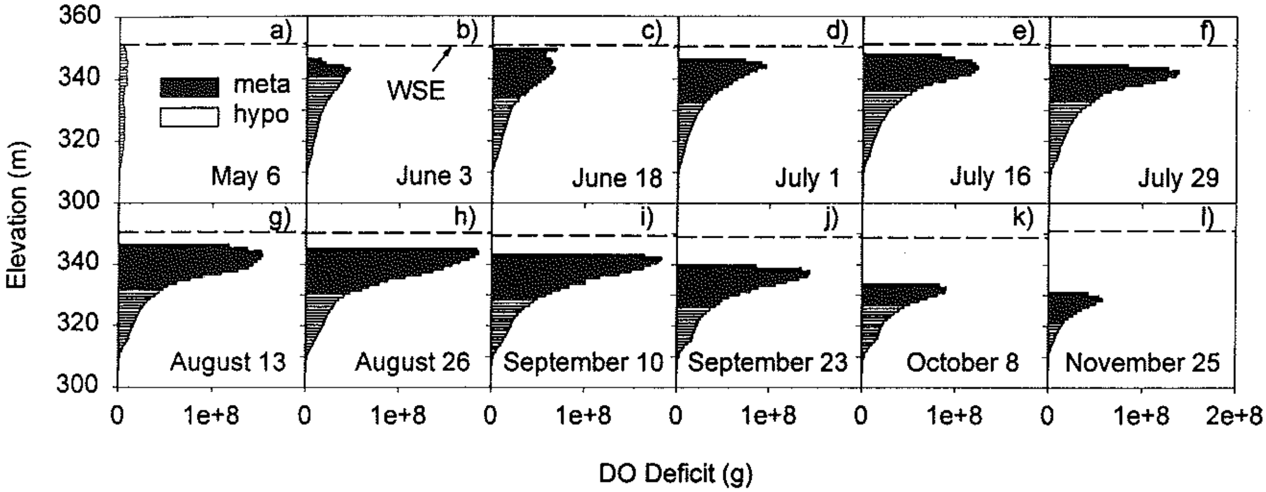

Figure 6.–Profiles of apparent DO mass deficit for site 1 for metalimnetic and hypolimnetic depths for 12 days in 1996: a) May 6, b) June 3, c) June 18, d) July 1, e) July 16, f) July 29, g) August 13, h) August 26, i) September 10, j) September 23, k) October 8, and l) November 25. Correspond with profiles of Figure 4.

Origins of Metalimnetic DO Minima in Cannonsville Reservoir

Relatively high concentrations of phytoplankton biomass occurred within the metalimnion of Cannonsville Reservoir during the summer of 1995. The peak concentration of the water column (Chl > 20 $\mu g \cdot L^{-1}$) occurred in the metalimnion on August 1, 1995 (Fig. 7a and b). This vertical pattern, or elevated concentrations extending from the surface into the metalimnion, was common for much of the summer stratification period. Though similar detailed profiling is unavailable for other years, we speculate that this vertical pattern may be recurring for the reservoir. Phytoplankton production of oxygen was largely limited to the epilimnion (Fig. 7c) because of the limited penetration of light (Effler et al. 1998). Respiration losses of oxygen (Fig. 7c) were predicted to approximately track the concentration of phytoplankton biomass (Auer and Forrer 1998, Doerr et al. 1998). Phytoplankton production of DO was predicted to exceed respiratory losses within the epilimnion for August 1, 1995 (Fig. 7c). The compensation depth (z_c; depth at which phytoplankton production equals respiration) was predicted to be ~ 5 m (Fig. 7d) on that day, nearly coinciding with $z_{0.01}$ and the upper boundary of the metalimnion (Fig. 7b). The higher net rates of oxygen consumption predicted for the metalimnion (Fig. 7d) compared to hypolimnetic layers for this DO sink process reflect the higher biomass concentrations of the metalimnion (Fig. 7a). Further, the minimum vertical mixing common to the metalimnion (Fig. 7e; e.g., Jassby and Powell 1975, Wodka et al. 1983) tends to preserve the effects of this localized sink process. Values of K_z for other days during summer stratification in 1995 establish that $z_{0.01}$ was above or at the depth of the metalimnion minimum (Fig. 8). Thus phytoplankton respiration contributed to depletion of DO within the metalimnion for most of the summer of 1995. Based on this analysis, we conclude that respiration/decay of phytoplankton within the metalimnion contributes to the occurrence of metalimnetic DO minima in Cannonsville Reservoir. Related activities of other communities, such as bacterial decay of dead phytoplankton and/or excreted organic carbon and localized zooplankton grazing, may amplify the DO depletion effects of phytoplankton respiration in the reservoir's metalimnion.

Two potential origins of the high phytoplankton concentrations of the reservoir's metalimnion are considered here, deposition from the overlying productive epilimnion (Auer and Forrer 1998, Doerr et al. 1998) and longitudinal transport through this layer of elevated concentrations entrained from the riverine zone (Effler and Bader 1998) as an interflow. The deposition source is favored, as analysis of transport characteristics of the reservoir does not support the interflow mechanism (Owens 1998b). Though there is evidence that the interflow phenomenon may occasionally occur in Cannonsville Reservoir, its specific features did not couple it to the observed metalimnetic DO minima of 1995. First, early development of the metalimnetic DO minimum was apparent in May of 1995 (Fig. 5) when the WBDR entered the reservoir as an overflow; i.e., before this inflow became negatively buoyant (starting in June, Owens 1998b). Owens (1998b) found that the WBDR would have entered the

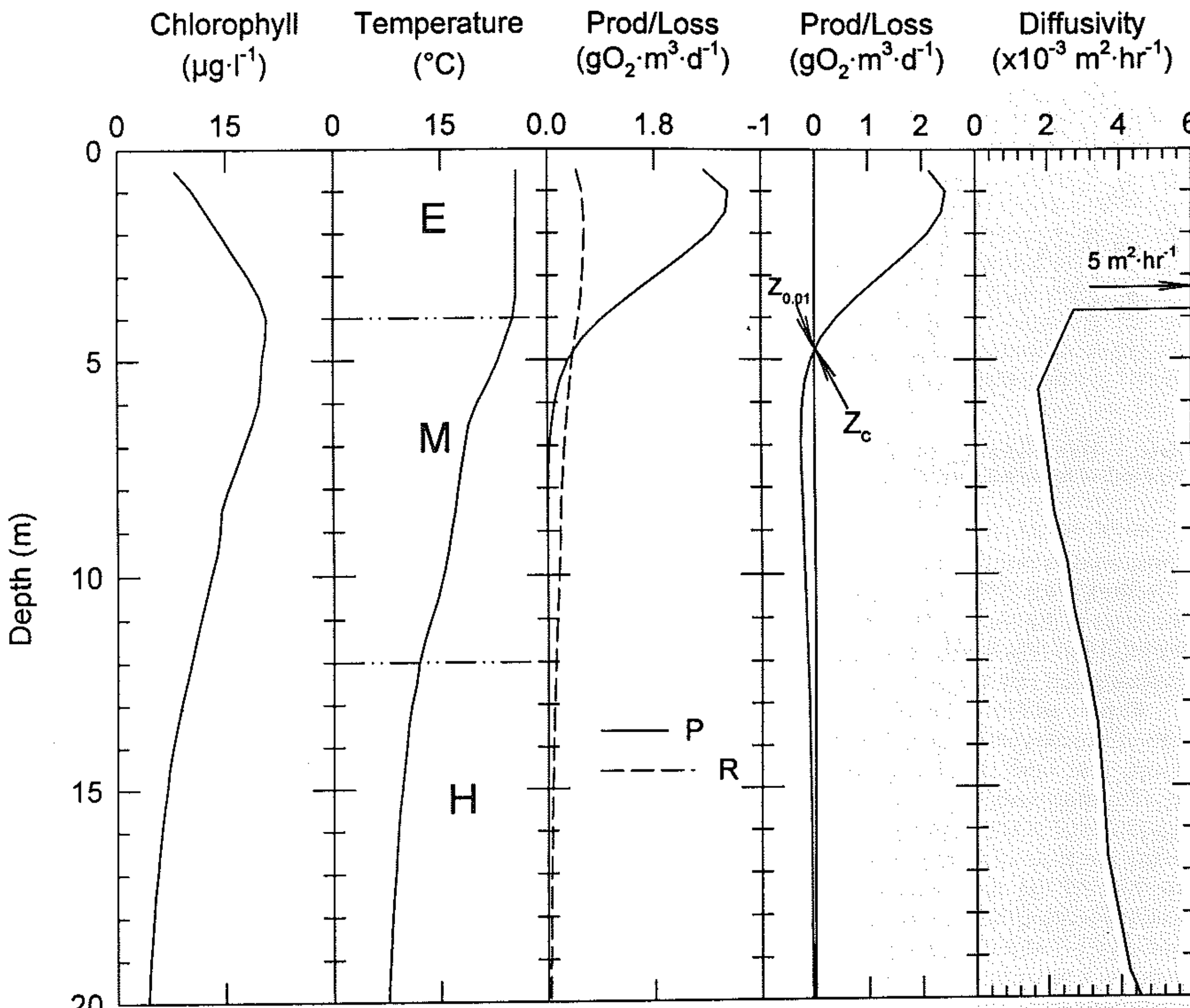

Figure 7.–Profiles for August 1, 1995: a) chlorophyll, b) temperature, c) photosynthetic production and respiration of DO, d) net photosynthetic production of DO and e) vertical diffusivity.

water column 3 to 6 m above the metalimnetic minimum DO concentration during the interval it was negatively buoyant. Further, detailed profiling for a number of parameters at multiple sites with the Seabird profiler failed to depict common signatures of the movement of an interflow through the system over the interval of the development of the DO minimum. Owens (1998b) concluded that the source for oxygen-demanding material within the depths of the metalimnetic minimum was not associated with an interflow from the WBDR.

Morphometric irregularities within stratified layers are almost certainly not a factor contributing to the recurring metalimnetic DO minima in Cannonsville Reservoir. First, no irregularities are manifested in hypsographic presentations of the reservoir's morphometry [see Fig. 2 in Owens et al. (1998)]. Second, such an effect is inconsistent with the rather uniform vertical position observed for the DO minimum with respect to the reservoir surface, despite the substantial interannual variations in extent of drawdown over the 1988-1997 interval (Fig. 3).

Partitioning DO Consumption Between the Metalimnion and Hypolimnion

On average, 70% of the DO consumption exerted below the epilimnion over the 1988-1997 interval occurred in the metalimnion (Fig. 9); the coefficient of variation (CV) for this contribution for the 10-year record was 17%. Variations in S_M explained nearly 90% of the interannual variations observed in the overall (S_M + S_H) consumption rate. The average summed

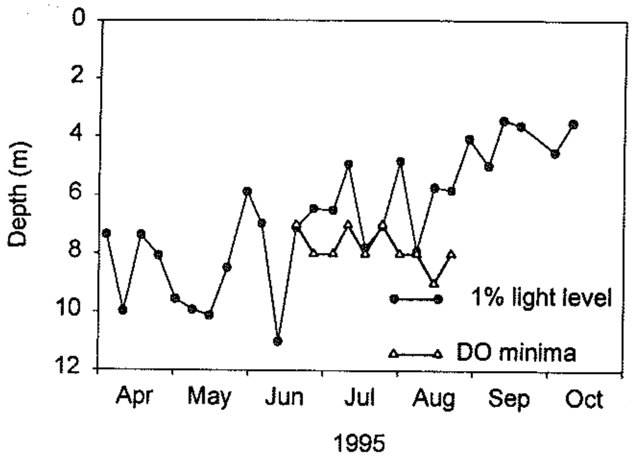

Figure 8.–Time series of $z_{\phi.01}$ (lower boundary of euphotic zone) and the depth of the metalimnetic DO minimum in 1995.

consumption rate for the period was ~ 13 tonnes·d⁻¹(t·d⁻¹), the CV was 29%. The magnitude of S_H contributed the most to the total in 1997 (~ 50%) and the least (~ 9%) in 1996 (Fig. 9), the year with the greatest overall consumption rate ($S_M + S_H > 20$ t·d⁻¹).

Export and entrainment are important components of the oxygen budgets of the reservoir's stratified layers, that have differed for the metalimnion and hypolimnion and year-to-year (Fig. 10). Thus, the signatures of DO depletion in the stratified layers of the lacustrine zone of this reservoir cannot be used as a measure of the metabolism of this system without accommodating these additional source/sink processes [see Eqs. (4) and (5)]. The components are resolved here for 2 years that represent extremes in reservoir operation (Fig. 10); 1995, a major drawdown year (Fig. 5), and 1996, a nearly full reservoir year (Fig. 4). The export sink of DO in the metalimnion was substantial relative to consumption in 1995, while this sink was much smaller in 1996 and minor relative to consumption (Fig. 10). Export was the dominant sink for DO in the reservoir's hypolimnion in both years (Fig. 10). Inputs of DO from entrainment were substantial in both 1995 and 1996 (Fig. 10). Entrainment inputs to the reservoir's hypolimnion were much greater in 1995 compared to the full reservoir case (Fig. 10), a recurring feature for years with major drawdowns. The rather small magnitude of S_H relative to entrainment inputs and export, and the residual (e.g., by difference) nature of the estimate of this consumption rate [Eq. (5)], suggests substantial uncertainty in the estimate.

Exertion of DO demand in hypolimna is generally assumed to be localized at the sediment-water interface, usually parameterized by sediment oxygen demand (SOD, g·m⁻²·d⁻¹; DiToro et al. 1990, Gelda and Auer 1996, Gelda et al. 1995). Consumption rates within the hypolimnion (S_H) have been normalized here by the interface area of this layer for each mass balance calculation interval to yield rates consistent with SOD. The average areal rate over the 10-year interval was 0.35 (±0.12) $g \cdot m^{-2} \cdot d^{-1}$, substantially less than the average value of SOD (~ 1.0 $g \cdot m^{-2} \cdot d^{-1}$) determined directly in laboratory experiments on undisturbed sediment core samples collected along the centerline of the reservoir (Erickson and Auer 1998). Our evaluation of potential origins of metalimnetic DO minima in the reservoir (e.g., Fig. 7) suggests the regulating processes are water column-based, leading to the representation of this DO consumption rate as a volumetric rate. Values of S_M were normalized according to the average volume of the layer over each calculation interval. The average rate for the 10-year period was 80 $mg \cdot m^{-3} \cdot d^{-1}$. If it is accepted that the more labile fraction of depositing organic particles is decomposed within the metalimnion (e.g., Wetzel 1983), it is reasonable to expect oxygen consumption rates in this layer to be more sensitive to interannual variations in primary production than hypolimnetic rates. However, no significant relationships between interannual variations of the volumetric rate of metalimnetic DO depletion and paired measures of trophic state (e.g., epilimnetic Chl and total dissolved P load in WBDR) were found.

The mass balance analysis [see Fig. 2, Eqs. (4) and (5)] has supported the partitioning of oxygen consumption between the metalimnion and hypolimnion for the rather complicated conditions that prevail in Cannonsville Reservoir. Uncertainties have been introduced associated with protocols adopted in data analysis and manipulations, and assumptions made within the framework of the mass balance analysis, including: 1) specification of boundaries of layers, 2) lack of detailed longitudinal resolution of hypo-

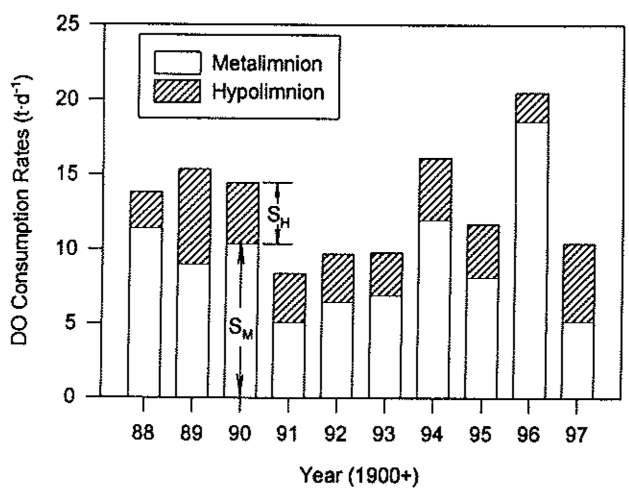

Figure 9.–Estimated average DO consumption rates within the metalimnion and hypolimnion over the spring to late summer interval, for years in the period 1988-1997.

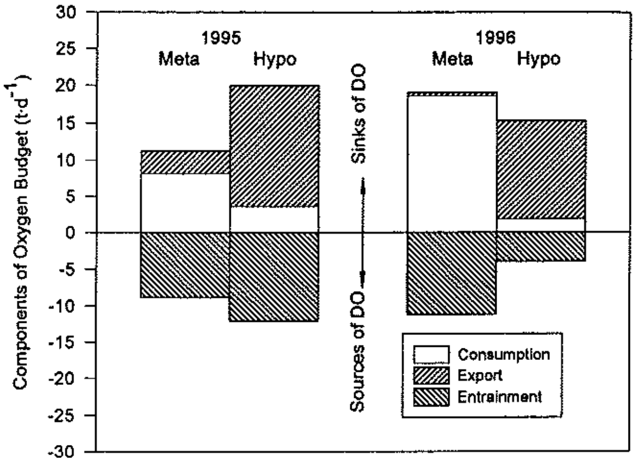

Figure 10.–Estimates of average DO consumption, export and entrainment rates in the metalimnion and hypolimnion for 1995 and 1996.

limnetic DO depletion within the lacustrine zone, 3) use of extrapolation to estimate DO concentrations in the deepest layers on several occasions, 4) assumption of α = 0.5 for calculations [see Eqs. (4) and (5)], 5) assumption of entry of inflows into the epilimnion, 6) assumption that small scale vertical mixing is minor relative to entrainment flows, and 7) use of time-averaged layer dimensions in calculations of normalized DO consumption rates. These protocols were supported by methodologies presented in the literature (e.g., Wetzel 1983, Doerr et al. 1996) as well as system-specific characterization (Gelda et al. 1998, Owens et al. 1998). Despite the limitations, the adopted protocol has yielded reasonable estimates of the partitioning of DO consumption between the metalimnion and hypolimnion for a reservoir with recurring metalimnetic minima and complex operational influences.

Significance of Metalimnetic DO Minimum

Metalimnetic DO minima have decreased to concentrations less than 4 mg·L^{-1} by late summer in every year over the 1988-1997 interval, and in certain years hypoxia was observed (e.g., Fig. 4). The depth intervals of these low concentrations have generally been ≥ 5 m thick; intervals of 10 m have been observed (e.g., Fig. 4). The prevailing vertical patterns of DO undoubtedly influence the distribution and movements of cold water fish in the reservoir.

The exertion of most of the oxygen demand of depositing seston within the metalimnion has important implications for the redox chemistry of the lower hypolimnion and related cycling between the underlying sediments and these bottom layers of the water column. For example, the bottom layers of portions of the lacustrine zone were anoxic for more than a month in 1995 (Effler and Bader 1998). The next most energetically favored electron acceptor to support decay processes, NO_3^- (Froelich et al. 1979, Kelly et al. 1988) was partially depleted, but not eliminated during this interval (Effler and Bader 1998). Thus, substantial releases of phosphorus (P) from the bottom lacustrine sediments, associated with the dissolution of ferric iron compounds (e.g., Mortimer 1941, 1971), did not occur. If the oxygen demand of depositing seston was instead primarily exerted at the reservoir bottom, as observed in most lakes and reservoirs (Cole 1994, Wetzel 1983), complete depletion of the hypolimnetic NO_3^- pool and subsequent release of sedimentary P would have been observed annually. Laboratory sediment release experiments, conducted under conditions of anoxia and elimination of NO_3^-, support this position (Erickson and Auer 1998).

The displacement of the exertion of oxygen demand to the shallower layers of the metalimnion also influences the timing of decreases in DO concentrations within the epilimnion that accompany the entrainment of depleted stratified layers with the approach to fall turnover. The prevailing vertical distributions of DO in the reservoir in late summer result in earlier entrainment of depleted layers compared to the case of depletions being localized within the hypolimnion. This encourages lower seasonal minima for the epilimnion during the approach to turnover, due to the higher temperature (i.e., lower DO saturation concentrations) of the upper layers in early fall compared to late fall (Effler and Bader 1998).

We are unaware of any nutrient-phytoplankton model, with water quality management goals, published in the literature, that accurately simulates metalimnetic DO minima driven by the slowed descent of settling seston (e.g., phytoplankton) in that layer. The model for Cannonsville Reservoir successfully simulates the time course of oxygen depletion below the epilimnion on a volume-weighted basis (Doerr et al. 1998), but fails to reproduce the details of the observed vertical distribution (Upstate Freshwater Institute 1997; e.g., particularly the metalimnetic minimum). Oxygen demand within the stratified layers of the reservoir in this model framework is localized at the reservoir bottom, parameterized as SOD (Doerr et al. 1998). The average value of SOD determined directly in laboratory experiments on undisturbed sediment core samples collected along the centerline axis of the reservoir (Erickson and Auer 1998) was applied uniformly across the sediment-water interface of the hypolimnion (Doerr et al. 1998). Based on the analysis presented here, it appears that the success of the model simulations of DO below the epilimnion, on a volume-weighted basis (Doerr et al. 1998), is an artifact of the coincidence of the DO demand represented by the applied SOD and the demand that is actually exerted within the metalimnion and at the sediment-water interface (Figs. 3-5). A model that successfully simulates the detailed vertical patterns of DO in Cannonsville Reservoir would necessarily represent the exertion of DO demand during the descent of seston and would have less SOD exerted. We hypothesize that the measurements of SOD (Erickson and Auer 1998) are actually applicable over a smaller area than presently assumed in the nutrient-phytoplankton model. This is at least in part supported by the lower value(s) of hypolimnetic DO consumption, normalized for interface area, reported here compared to the measurements of SOD.

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References

Auer, M. T. and B. E. Forrer. 1998. Development and parameterization of a kinetic framework for modeling light- and phosphorus-limited phytoplankton growth in Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):290-300.

Birge, E. A. and C. Juday. 1911. The inland lakes of Wisconsin. The dissolved gases and their biological significance. Bull. Wisc. Geol. Nat. Hist. Surv. 22:1-259.

Cole, G. A. 1994. Textbook of limnology. Fourth edition. Waveland Press, Inc., Prospect Heights, IL.

Cole, T. M. and H. H. Hannon. 1990. Dissolved oxygen dynamics. P. 71-107. *In:* K.W. Thorton, B. L. Kimmel and F. E. Payne (eds.). Reservoir limnology, ecological perspectives. John Wiley & Son, New York.

DiToro, D. M., R. P. Paquin, K. Subburamu and D. A. Gruber. 1990. Sediment oxygen demand model: methane and ammonia oxidation. J. Environ. Eng. 116:945-986.

Doerr, S. M., S. W. Effler and E. M. Owens. 1996. Forecasting impacts of a hypolimnetic wastewater discharge on lake water quality. Lake and Reserv. Manage. 12:207-217.

Doerr, S. M., E. M. Owens, R. K. Gelda, M. T. Auer and S. W. Effler. 1998. Development and testing of a nutrient-phytoplankton model for Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):301-321.

Drury, D. D. and R. A. Gearheart. 1975. Bacteria population dynamics and dissolved oxygen minimum. J. Am. Water Works Assn. 67:154-158.

Effler, S. W. and A. P. Bader. 1998. A limnological analysis of Cannonsville Reservoir, NY. Lake and Reserv. Manage. 14(2-3):125-139.

Effler, S. W., M. G. Perkins and D. L. Johnson. 1998. The optical water quality of Cannonsville Reservoir: spatial and temporal patterns, and the relative roles of phytoplankton and inorganic tripton. Lake and Reserv. Manage. 14(2-3):238-253.

Erickson, M. J. and M. T. Auer. 1998. Chemical exchange at the sediment-water interface in Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):266-277.

Froelich, P. N., G. P. Klinkhammer, M. L. Bender, N. A. Luedtke, G. R. Health, D. Cullen, P. Dauphin, D. Hammond, B. Hartman and V. Maynard. 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis. Goechim. Cosmochom. Acta. 43:1075-1090.

Gelda, R. K. and M. T. Auer. 1996. Development and testing of a dissolved oxygen model for Onondaga Lake. Lake and Reserv. Manage. 12:165-179.

Gelda, R. K., M. T. Auer and S. W. Effler. 1995. Determination of sediment oxygen demand by direct measurement and by inference from reduced species accumulation. Mar. Freshwat. Res. 46:81-88.

Gelda, R. K., E. M. Owens and S. W. Effler. 1998. Calibration, verification, and an application of a two-dimensional hydrothermal model [CE-QUAL-W2(t)] for Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):186-196.

Gordon, J. A. and B. A. Skelton. 1977. Reservoir metalimnion oxygen demands. J. San. Eng. Div. Proc. ASCE 103:1001-1016.

Hutchinson, G. E. 1957. A treatise of limnology. Vol. I. Geography, physics and chemistry. John Wiley and Sons, New York.

Jassby, A. and T. M. Powell. 1975. Vertical patterns of eddy diffusion during stratification in Castle Lake, California. Limnol. Oceanogr. 20:530-543.

Kelly, C. A., J. W. M. Rudd and D. W. Schindler. 1988. Carbon and electron flow via methanogenesis, reduction in anoxic hypolimnion of three lakes. Arch. Hydrobiol. Beih. Ergebn. Limnol. 31:333-344.

Kirk, J. T. O. 1994. Light and photosynthesis in aquatic ecosystems. 2nd edition. Cambridge University Press, Cambridge.

LaBounty, J. F. and M. J. Horn. 1997. The influence of drainage from the LasVegas Valley on the limnology of Boulder Basin, Lake Mead, Arizona-Nevada. Lake and Reserv. Manage. 13:95-108.

Longabucco, P. and M. Rafferty. 1998. Analysis of material loading to Cannonsville Reservoir: advantage of event-based sampling. Lake and Reserv. Manage. 14(2-3):197-212.

Martin, J. L. 1988. Application of a two-dimensional water quality model. J. Environ. Eng. ASCE. 114:317-326.

Mitchell, S. F. and C. W. Burns. 1979. Oxygen consumption in the epilimnia and hypolimnia of two eutrophic warm-monomictic lakes. New Zealand J. Mar. Freshwat. Res. 13:427-441.

Mortimer, C. H. 1941. The exchange of dissolved substances between mud and water (Parts I and II). J. Ecol. 29:280-329.

Mortimer, C. H. 1971. Chemical exchanges between the sediments and water in the Great Lakes–speculation on probable regulatory mechanisms. Limnol. Oceanogr. 16:387-404.

Nix, J. 1981. Contribution of hypolimnetic water to metalimnetic dissolved oxygen minima in a reservoir. Wat. Resour. Res. 17:329-332.

Owens, E. M. 1998a. Thermal and heat transfer characteristics of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):152-161.

Owens, E. M. 1998b. Identification and analysis of hydrodynamics and transport characteristics of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):162-171.

Owens, E. M. 1998c. Development and testing of one-dimensional hydrothermal models of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):172-185.

Owens, E. M., R. K. Gelda, S. W. Effler and J. M. Hassett. 1998. Hydrologic analysis and model development for Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):140-151.

Shapiro, J. 1960. The cause of a metalimnetic minimum of dissolved oxygen. Limnol. Oceanogr. 5:216-227.

Upstate Freshwater Institute. 1997. Cannonsville Reservoir modeling project. Prepared for New York City Department of Environmental Protection. Valhalla, NY.

Walker, W. W. 1987. Empirical methods of predicting eutrophication in impoundments. Report 4: Phase III: Applications manual Technical report E-81-9. US Army Waterways Experimental Station. Vicksburg, MS.

Walker, W. W. 1979. Use of hypolimnetic oxygen depletion rate as a trophic state index for lakes. Wat. Resour. Res. 15:1463-1470.

Welch, E. B. and M. A. Perkins. 1979. Oxygen deficit-phosphorus loading relationship in lakes. J. Wat. Pollut. Contr. Fed. 51:2823-2828.

Wetzel, R. G. 1983. Limnology, 2nd edition. Saunders College Publishing, Philadelphia, PA.

Wetzel, R. G. and G. E. Likens. 1991. Limnological analysis (2nd edition). Springer-Verlag, New York.

Wodka, M. C., S. W. Effler, C. T. Driscoll, S. D. Fields and S. P. Devan. 1983. Diffusivity-based flux of phosphorus in Onondaga Lake. J. Environ. Eng. ASCE 109:1403-1415.