Development and Testing of One-Dimensional Hydrothermal Models of Cannonsville Reservoir[1]

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ABSTRACT

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Two one-dimensional (vertical) hydrothermal models of Cannonsville Reservoir, a water supply serving New York City, were developed and tested. A two-layer model, capable of hindcasting temperature dynamics for two (epilimnion, hypolimnion) completely-mixed, variable-volume layers, was calibrated by determining the seasonal variation of the vertical heat transfer coefficient. This model was used only to hindcast temperature for the spring-fall period of 1995. A multi-layer model (average layer thickness 1.5 m over 50 m maximum depth) was developed that has the capability of forecasting stratification and vertical transport conditions in the reservoir based on specified meteorologic, hydrologic, and reservoir operation conditions. As a part of calibration, the multi-layer model was used to hindcast stratification and vertical transport conditions for the continuous period 1988 through 1995. The model accurately reproduced observed temperature profiles and other observed features such as thermocline depth, rate of hypolimnetic heating, and duration of stratification. A sensitivity analysis indicated that vertical transport of heat to the lower waters of the reservoir in summer is largely associated with advection caused by release of water at the base of the dam; vertical diffusion plays a relatively small role. Model forecasts indicate that stratification characteristics are relatively insensitive to intake location (three intakes over a range of elevation are available), but are more sensitive to the rate of dam release.

Key Words: hydrothermal model, stratification, vertical mixing.

Owned and operated by the New York City Department of Environmental Protection, Cannonsville Reservoir is used to supply drinking water for New York City and to store water for subsequent release to the Delaware River downstream of the dam during low flow. The reservoir is 27 km long (Fig. 1) and has maximum and mean depths of 50 and 19 m, respectively. The reservoir is dimictic, and thus experiences complete mixing during the spring and fall in response to annual meteorological variations. The reservoir receives inflow from a large watershed, with the West Branch of the Delaware River (WBDR) being the largest tributary. Water leaves the reservoir over a spillway, through one of three drinking water intakes, and by release to the WBDR through conduits located near the base of the dam (Table 1). Depending on runoff from the watershed and release and water supply requirements, there are significant seasonal and interannual variations in reservoir storage. The reservoir has been classified as eutrophic (Effler and Bader 1998). Management of the associated water quality problems in the reservoir is a primary goal for this modeling program. Analysis of historical data indicates a linkage between measures of eutrophication-related water quality degradation and reservoir drawdown (Effler and Bader 1998). To increase understanding of this linkage, mechanistic models of surface water quality can be used.

Mechanistic models of surface water quality are based on the principle of conservation of mass, and in some cases other conservation equations (Thomann and Mueller 1987). In addition to biochemical processes, the physical processes of mass transport are generally included in such models. The magnitude of transport processes must either be determined by predictive equations or identified for a particular water body from observations in order for realistic model solutions to be computed. Due to the potentially strong impact of thermal stratification on water motion and transport (Fischer et al. 1979), lake and reservoir

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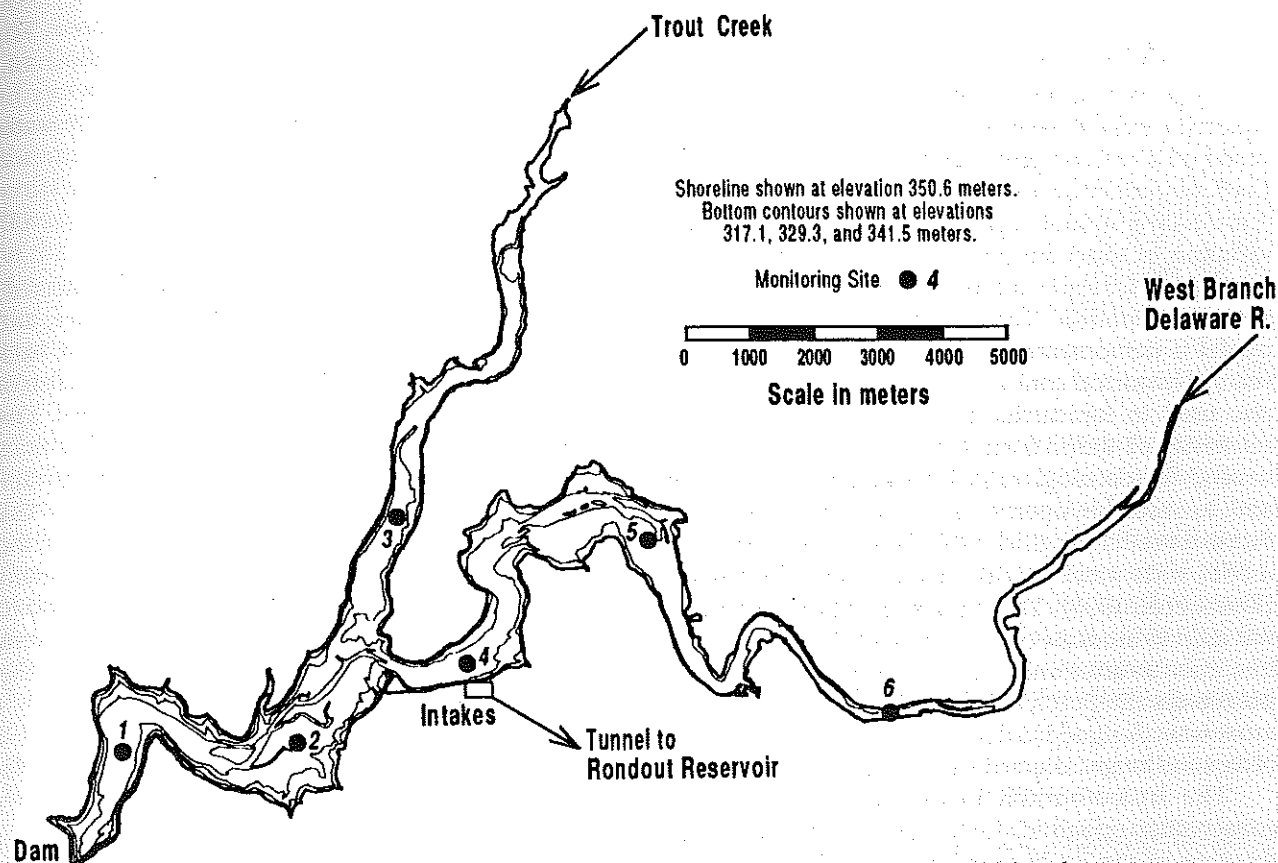[1] Contribution No. 173 of the Upstate Freshwater Institute.

Figure 1.–Site map of Cannonsville Reservoir, showing monitoring sites, tributaries, and drinking water withdrawal.

models that are designed to predict transport must also consider temperature dynamics and have been described as hydrothermal models (Harleman 1982). Hydrothermal models typically consider basin bathymetry, meteorologic and hydrologic conditions, and reservoir operations in generating predictions of water motion, mixing, and temperature distribution over space and time. The one-dimensional

Table 1.–Top and bottom elevations of the opening of various structures associated with outflow from Cannonsville Reservoir. The spillway elevation is that of the crest.

Structure	Elevation (m)	
	Top of Opening	Bottom of Opening
Spillway	—	350.6
High Intake	342.0	339.5
Middle Intake	333.2	328.6
Low Intake	323.8	317.1
Dam Release	306.7	304.6

hydrothermal models described herein are designed for application to reservoirs that consider spatial variations only in the vertical direction.

Cannonsville Reservoir has undergone monitoring of conditions that is sufficient for hydrothermal model testing beginning in 1988 (Owens 1998a). Water quality monitoring over the same period has shown that the dominant spatial variations in constituents associated with eutrophication are in the vertical direction, with only modest variations in the longitudinal direction (Effler and Bader 1998; Owens 1998a). Motivated by the goal of development of a model or models capable of reproducing observed conditions, one-dimensional (vertical) and two-dimensional (vertical-longitudinal) hydrothermal models have been developed and tested for the reservoir. The development and testing of the two-dimensional hydrothermal model are described elsewhere (Gelda et al. 1998), as is the eutrophication model (Doerr et al. 1998). The utility of the multi-layer hydrothermal model in assessing water quality management options for the reservoir is demonstrated by the incorporation of vertical transport processes that have been found to be important in previous studies (Harleman 1982, Owens and Effler 1989, Owens and Effler 1996), and by its accurate hindcasting for 8 continuous years of historical conditions.

Model Development

Two hydrothermal models for Cannonsville Reservoir were developed. Both of these models are based on a one-dimensional (vertical) assumption, so that longitudinal or lateral variations are not considered. A multi-layer model, capable of predicting the vertical variation of water motion, mixing, and temperature over the entire water column, is the more important of these two models. The accuracy of the multi-layer model is demonstrated by hindcasting 8 continuous years of historical conditions. The multi-layer model is also used in forecasting in order to investigate the sensitivity of thermal stratification characteristics to natural meteorologic and hydrologic characteristics and to reservoir operations. The multi-layer hydrothermal model serves as the basis for a eutrophication model with water quality management capabilities (Doerr et al. 1998). The more simple two-layer model was used to hindcast conditions for 1995 and was used in a mass balance analysis of trihalomethane (THM) precursors (Stepczuk et al. 1998). Both hydrothermal models are designed to describe variations over periods of days and longer; diurnal variations are not considered.

The hydrothermal models are based on the conservation equations for heat, water volume, and, in the case of the multi-layer model, turbulent kinetic energy. The one-dimensional equations assume that temperature, vertical water motion, and mixing are uniform in the horizontal plane and vary only in the vertical direction and over time. The one-dimensional heat conservation equation is given by

$$\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = \frac{1}{A}\frac{\partial}{\partial z}\left(A\,K\frac{\partial T}{\partial z}\right) + \frac{1}{\rho c A}\frac{\partial}{\partial z}(A\phi_s)$$

$$+ \frac{1}{A}\Sigma q_I(T_I - T) \qquad (1)$$

where T is water temperature, t is time, w is the vertical velocity, z is vertical position, A is the plan area of the lake basin, K is the turbulent diffusion coefficient, ρ and c are the density and specific heat of water, ϕ_s is the flux of solar radiation in the water column, q_I is the inflow per unit vertical distance, and T_I is the inflow temperature. The summation in the inflow term indicates that the characteristics of three inflow sources are considered. These inflows are WBDR, Trout Creek, and the remaining smaller tributaries lumped together as a single inflow source (Owens et al. 1998). The vertical velocity w is determined from the areally averaged continuity equation for the basin, given by

$$w = \frac{1}{A}\int_0^z (q_I - q_o)\, dz \qquad (2)$$

where q_o is the outflow per unit vertical distance. The quantities q_I and q_o are determined by inflow and withdrawal submodels which are described below.

The boundary condition for Eq. 1 at the water surface ($z = z_s$) is

$$-\rho c K\frac{\partial T}{\partial z} = \beta\phi_{SN} + \phi_{AN} + \phi_B + \phi_E + \phi_C \text{ at } z = z_s \qquad (3)$$

where β is the fraction of the net (incident less reflected) solar radiation ϕ_{SN} adsorbed at the water surface, and ϕ_{AN}, ϕ_B, ϕ_E, and ϕ_C are net atmospheric radiation, back radiation, evaporative, and conductive components of heat transfer at the water surface, respectively. The components of water surface heat transfer are functions of meteorological conditions and water surface temperature, and have been evaluated for the Cannonsville site (Owens 1998a). During ice cover, the expressions for the surface heat transfer components are modified to account for the presence of ice and to allow prediction of ice thickness (Ashton 1986; Owens and Effler 1996). The flux of solar radiation in the water column ϕ_s is related to ϕ_{SN} by

$$\phi_s = (1 - \beta)\,\phi_{SN}\,e^{-k_D(z_s - z)} \qquad (4)$$

where k_D is an extinction coefficient.

Two-Layer Model

The two-layer model is based on integration of Eq. 1 over depth from the reservoir bottom to the thermocline (hypolimnion) and from the thermocline to the water surface (epilimnion). The volumes of the epilimnion and hypolimnion may change over time due to imbalance in inflow and outflow, and also as a result of deepening or shallowing of the epilimnion associated with wind mixing and surface heating and cooling. In order to maintain a water balance for each layer, water may flow across the thermocline (Auer et al. 1997). Combining water and heat balance equations for each layer yields the following temperature equations

$$V_E\frac{d}{dt}(T_E) = Q_{IE}(T_I - T_E) + A_T[w_T(T^* - T_E) - v_T(T_E - T_H)]$$

$$+ \frac{A_s}{\rho c}[\phi_{SN} + \phi_{AN} + \phi_B + \phi_E + \phi_C] \qquad (5a)$$

$$V_H\frac{d}{dt}(T_H) = Q_{IH}(T_I - T_H) - A_T[w_T(T^* - T_H) - v_T(T_E - T_H)]$$

$$\qquad (5b)$$

where V is layer volume, Q_I is tributary inflow, T_I is tributary temperature, A_T and A_s are the plan area of

the thermocline and water surface, w_T is the vertical velocity across the thermocline, T^* is the temperature of water moving across the thermocline, and v_T is a transfer coefficient representing diffusion across the thermocline. The subscripts E and H designate properties of the epilimnion and hypolimnion, respectively. It is assumed in Eq. 5 that all solar radiation is adsorbed in the epilimnion. The position of the thermocline is determined from observed temperature profiles at site 1 (Fig. 1), and is assumed to be located at the maximum vertical temperature gradient, neglecting any diurnal stratification.

The two-layer model requires the position of the thermocline to be specified; for the hindcasting application described here, this position is determined from measurements. Combining the thermocline position information with hypsographic data for the basin and the variation of total volume ($V_E + V_H$), the variation of V_E and V_H individually over time can be computed (Eq. 5). The vertical velocity at the thermocline w_T is then determined based on a water balance for each layer. The lack of a predictive procedure for determining the thermocline position, layer volumes, and w_T in the two-layer model is consistent with its limited use in hindcasting of observed conditions.

The two-layer model uses the simple assumption that all inflows enter and mix with the surface layer. It is also assumed that spillway flow occurs from the surface layer, dam release occurs from the bottom layer, and drinking water withdrawal is from the layer in which the active intake is located (Owens 1998b). While the transfer coefficient v_T in the two-layer model could be determined by a predictive equation, the use of this model for hindcasting allowed the time variation of v_t to be determined by calibration. The temperature equations for the two layers (Eq. 5) are integrated using an implicit procedure with a time step of 1 day, and initial conditions for T_E and T_H determined from temperature profiles from the first day of field monitoring in the spring of 1995.

Multi-Layer Model

Dynamics of the mixed layer (epilimnion)

The multi-layer model is an integral model, which assumes a well-mixed layer of depth h exists at the reservoir surface. The depth and temperature of this layer are determined by conservation equations for turbulent kinetic energy and heat which have been integrated over the depth of this layer. The variation of h is determined from the value of the velocity scale σ defined by

$$\sigma^3 \equiv \eta^3 \, u_*^3 + w_*^3 \tag{6}$$

where u_* is the shear velocity due to wind stress at the water surface (related to wind speed; set to zero with ice cover), w_* is a velocity scale which considers buoyancy effects, and η is a dimensionless coefficient (Table 2). When the water surface is cooling, penetrative convection acts as a source of turbulent mixing and $w_* > 0$, while surface heating causes turbulence to be damped in the mixed layer and $w_* < 0$. If $\sigma > 0$, then excess turbulent kinetic energy is available for the mixed layer to deepen, which is defined by

$$\frac{dh}{dt} + \frac{C_F \sigma}{C_T + Ri} + \frac{1}{A_B}(Q_i - Q_o) \tag{7}$$

where $Ri = \sigma^2 / (\Delta \rho \, g \, h)$ is the bulk Richardson number for the layer, $\Delta \rho$ is the density increment at the base of the mixed layer, g is the acceleration of gravity, Q_i and Q_o are inflow to and outflow from the mixed layer, A_B is the area at the base of the mixed layer, and C_F and C_T are additional coefficients (Table 2). If $\sigma < 0$, the mixed layer depth h is reduced until $\sigma = 0$, indicating that energy input from wind mixing is balanced by the changes in potential energy associated with warming of the mixed layer.

Inflow mixing and placement

All inflow to Cannonsville Reservoir occurs in stream channels entering at the shoreline. The density of such inflows relative to the surface waters of the reservoir determines the manner of mixing of such inflowing waters (Alavian et al. 1992). Measurements of temperature, conductivity, and suspended solids in the major inflows to the reservoir, and in the reservoir itself, indicate that significant density differences are due to temperature only (Owens 1998b). In addition, temperature measurements indicate that WBDR and Trout Creek tend to be warmer (buoyant) relative to reservoir surface waters in spring and early summer, but cooler in mid-summer through fall (Owens 1998a).

If the inflow density is less than that of reservoir

Table 2.–Summary of hydrothermal model coefficients.

Coefficient	Used in Equation(s)	Value	Source
β	3 and 4	0.4	Harleman (1982)
η	6	1.3	Calibration
C_F	7	0.5	Aldama et al. (1988)
C_T	7	0.36	Aldama et al. (1988)
C_D	8	0.016	Alavian et al. (1992)
C_H	12	4×10^{-4}	Calibration
r	12	0.3	Calibration

Note: all coefficients are dimensionless.

surface waters, an overflow occurs wherein the inflow waters spread out over the reservoir surface near the mouth of the tributary, where wind-driven processes generally mix the inflowing water with ambient surface water (Alavian et al. 1992). The additional energy that is required to mix buoyant inflow into the mixed layer is included in the velocity scale w_* (Eq. 6), while its effect on the mixed layer depth and volume is included in the term containing Q_t (Eq. 7).

However, if the inflow density is greater than the surface waters, the stream will plunge below the surface of the reservoir as a distinct density current, flowing down the sloping reservoir bottom while entraining ambient water from the water column of the reservoir (Alavian et al. 1992). When the inflow density, reduced by such entrainment, is equal to that in the reservoir at a particular depth, the density current lifts away from the reservoir bottom and intrudes horizontally into the water column as an interflow. The inflowing water and associated heat and mass effectively enter the water column at the interflow depth.

For conditions in Cannonsville Reservoir where inflow is more dense than the reservoir surface waters, the theory of Hebbert et al. (1979) is used. This theory assumes a lateral cross section of the stream or reservoir is of triangular shape, which is well-suited to the geometry of the reservoir. The nature of the negatively-buoyant density current is described by the densimetric Froude number $F = u/\sqrt{g'H}$, where u is the velocity of the current, $g'=g(\rho_I - \rho_S)/\rho_S$ is the reduced gravity of the underflow, ρ_I is the inflow density, ρ_S is the reservoir density, and H is the depth of the current. It is assumed the density current maintains a "normal" depth, such that the force of gravity driving the flow is balanced by friction and entrainment. The normal flow assumption implies that F is given by

$$F^2 = \frac{S \tan (\alpha/2)}{C_D} (1 - 0.85 \, S\sqrt{C_D}) \tag{8}$$

where S is the slope of the river channel, α is base angle of the assumed triangular channel, and C_D is a drag coefficient describing friction between the current and reservoir bottom (Table 2). Entrainment of reservoir water into the density current increases its flow rate and modifies its density (buoyancy). Entrainment is described by

$$\frac{dQ}{dx} = E \, u \, b \tag{9}$$

where Q is the flow rate of the density current, E is a dimensionless entrainment coefficient, b is the width of the underflow, and x is distance along the river channel. The theory of Hebbert et al. (1979) defines $E = 1.6 \, C_D^{3/2} F^2$.

For plunging conditions, Eqs. 8 and 9 are solved to compute the variation of characteristics of the density current. The inflow density ρ_I is modified by entrainment, and the reduced gravity g' decreases as the current moves down the sloping reservoir bottom. The interflow forms at the depth where $g'=0$, and the inflow together with entrained reservoir water from higher elevation enters the water column of the reservoir.

Outflow mechanics

Experimental observations and theoretical studies (Bohan and Grace 1973, Davis 1987) indicate that outflow structures draw from the water column of a reservoir over a range of elevation which extends above and below the elevation of the structure itself. The range of elevation depends on the geometry of the structure, the local bathymetry of the reservoir, the outflow rate, and the local stratification in the reservoir. Based on these studies, the multi-layer model computes this range individually for each of the three forms of outflow from Cannonsville Reservoir, which determines the outflow distribution q_o (Eq. 2).

Spillway flow from the reservoir occurs in an uncontrolled manner when the reservoir level exceeds the elevation of the spillway crest (Table 1). The range of depth from which the spillway draws is determined by assuming that flow over the spillway occurs through a slot whose width is equal to the spillway length L. The spillway draws water from the surface down to a depth h_s computed from

$$h_s = \left(\frac{4 \rho Q^2}{\Delta \rho \, g \, L^2} \right)^{1/3} \tag{10}$$

where Q is the rate of spillway outflow, and $\Delta\rho$ is the density difference between the reservoir surface and the depth h_s. The two remaining forms of outflow, those being drinking water withdrawal and dam release, occur through submerged ports. The multi-layer model assumes the range of elevation from which these two outflows draw water is defined by

$$\Delta z = \left(\frac{\rho Q^2}{\Delta \rho \, g} \right)^{1/5} \tag{11}$$

where Δz is the vertical distance from the elevation of the outflow structure to the upper or lower range of outflow, and $\Delta\rho$ is the density difference in the water column over Δz. Dam release occurs through a series of pipes whose invert elevation is 3.4 m above the deepest point of the reservoir. Due to this small distance and the small reservoir volume below the elevation of the release pipes, it is assumed the outflow range for dam release extends downward to the reservoir bottom; Eq. 11 was used to determine the upper limit of the

outflow range. For the drinking water withdrawal, Eq. 11 was used to determine both the lower and upper ranges of outflow.

Vertical diffusion

The turbulent diffusion coefficient K (Eq. 1) quantifies mixing between adjacent layers in the water column. While specific relationships vary, lake and reservoir models generally assume that diffusion is driven by wind shear at the water surface, and is damped in the water column by stable stratification (Fischer et al. 1979, Rodi 1987, Aldama et al. 1988). The relationship used in the multi-layer model is

$$K = C_H \frac{A_s u_*^2}{V_T N^r} \tag{12}$$

where C_H and r are empirical coefficients (Table 2), A_s is the surface area of the reservoir, V_T is the total volume of the reservoir, and N is the local buoyancy frequency in the water column defined by $N^2 = -(g/\rho)(\partial \rho / \partial z)$. Thus, the diffusion coefficient K is a function of both depth and time.

Numerical solution

The water column is discretized into layers that varied in thickness from 0.8 to 2.0 m. Vertical advection was simulated using a Lagrangian procedure, wherein individual layers were allowed to expand and contract in thickness within these limits and move vertically in response to the vertical distribution of q_I and q_O determined from the inflow and outflow components of the model described above. Diffusion was computed at the interface between adjacent layers with Eq. 12, using an implicit, centered-difference technique. The resulting difference equations were integrated using a time step of 1 day, so that all model inputs were specified as daily averages.

Model Inputs and Calibration

The hydrothermal models require bathymetric, hydrologic, and meteorologic data for the Cannonsville Reservoir site in order to perform hindcast simulations of historical conditions. Bathymetric data for both models were determined from analysis of topography prior to reservoir construction (Gorokhovich et al. 1996). The imbalance between reservoir inflow and outflow (Fig. 2a) determines the change in storage and resulting drawdown and refilling of the reservoir. Inflow temperature measurements (Owens 1998a) indicate

seasonal differences relative to reservoir surface waters, such that buoyant overflows and plunging inflows occur at various times of the year (Fig. 2b). All outflow rates and the WBDR inflow rate are measured; inflow from the ungaged tributaries was determined from a reservoir water balance (Owens et al. 1998).

Meteorological data was measured at the Cannonsville Dam during 1995. Daily average dry bulb and dew point air temperatures (Fig. 2c), wind speed (Fig. 2d) and incident solar radiation (Fig. 2e) are used to determine surface heat transfer and energy for mixing. Prior to 1995, measurements at the National Weather Service station at Binghamton (located 64 km west) were used. An analysis of daily average measurements at Cannonsville Dam and Binghamton for 1995 showed a very good comparison, with the exception of wind speed. An empirical relationship was developed from the 1995 data to allow prediction of onsite wind speed from measurements at Binghamton for 1988-1994 (Gelda et al. 1998). As no incident solar radiation measurements are made at Binghamton, a predictive formula was used to estimate solar radiation based on latitude, longitude, time, and cloud cover fraction for 1988-1994 (Owens 1998a). The extinction coefficient k_D (Eq. 4) was determined from underwater light measurements. All hydrothermal model simulations begin on January 1, assuming that the water column is at the uniform temperature of 4 °C. The boundary conditions for the model are thus tributary inflow rates (Eqs. 1, 2, 7, 8, 9), inflow temperature (Eq. 1), outflow rates (Eqs. 2, 7, 10, 11), wind (Eqs. 3, 6, 12), and other meteorological conditions (Eq. 3).

Multi-layer model calibration was carried out by comparing predicted temperatures for 1994 and 1995 to measurements. Temperature profiles measured at site 1 (Fig. 1) were used for this purpose. Profiles were measured about once per month in the early years of monitoring, increasing to weekly in 1995 (Owens 1998a). The multi-layer model coefficient values determined by calibration are the wind mixing coefficient η (Eq. 6), and the coefficients C_H and r in the expression for the turbulent diffusion coefficient K (Eq. 12). The wind mixing coefficient η was adjusted so that the mixed layer and thermocline depths were predicted accurately. The coefficients C_H and r were adjusted so that lower water temperatures agreed with measurements. The coefficient values determined in calibration (Table 2) were then validated in a continuous simulation for 1988 through 1995. The two-layer model was calibrated for the spring-fall interval of 1995 by determining the time variation of the transfer coefficient v_T. A constant value of v_T was determined for each 1-week period between consecutive measurements so that predicted layer temperatures accurately reproduced measurements.
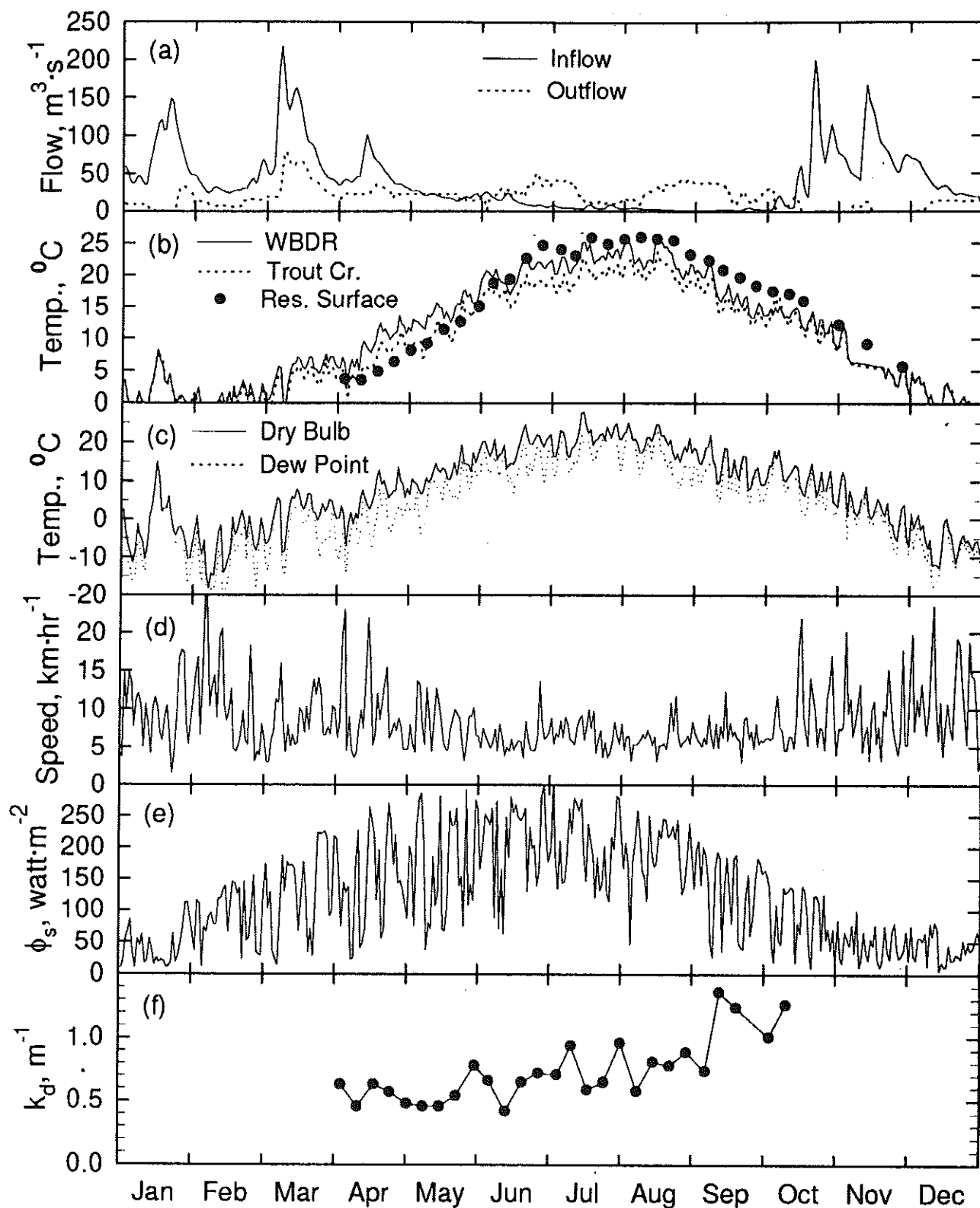
Figure 2.–Selected model inputs for 1995: a) total reservoir inflow and outflow (Flow, $m^3 \cdot s^{-1}$); b) the West Branch of the Delaware River and Trout Creek temperature determined from measurements and empirical model, and measured reservoir surface (Res. Surface) temperature (Temp., $^\circ$C); c) dry bulb and dew point air temperatures (Temp., $^\circ$C); d) wind speed (Speed, km · hr^{-1}); e) incident solar radiation (ϕ_s, watt · m^{-2}); and f) measured light extinction coefficient (k_d, m^{-1}).

Model Hindcasting Results

The two-layer model model accurately predicted (rms error = 0.9 °C) epilimion and hypolimnion temperatures for 1995 (Fig. 3a). The accurate prediction for the epilimnion indicates that surface heat transfer is simulated well by the model. The predicted hypolimnion temperature is sensitive to the selected value of the transfer coefficient v_T only in spring and fall, when thermal stratification is weak; during summer, vertical advection (w_T in Eq. 5) dominates heat transfer and the rate of heating of the hypolimion. The seasonal variation of the transfer coefficient v_T (Fig. 3b), determined by calibration, is highest in spring and fall and small in summer when thermal stratification is strong.

While adequate monitoring data for testing of the multi-layer model were available for all 8 years, the most comprehensive data were collected in 1995. In addition, testing of the eutrophication model was based on hindcasting for 1994 and 1995, with a monitoring program in 1995 that was specifically designed to support eutrophication model testing (Doerr et al. 1998). As a result, emphasis is placed on 1995 for evaluation of performance of the multi-layer model.

The primary basis for evaluation of the hydrothermal model was reproduction of temperature profiles measured at site 1 (Fig. 1). Model predictions of temperature profiles for 1995 (Fig. 4) indicate good model performance. Features of the thermal stratification that were simulated accurately include surface temperature, mixed layer depth, near-bottom temperature, and overall profile shape. In order to summarize the predicted temperature profiles for the entire 8-year period, volume-weighted average temperatures for the portion of the water column above (epilimnion) and below (hypolimnion) the thermocline were computed from predicted and measured temperature profiles. The predicted epilimnion and hypolimnion temperatures from the continuous 8-year simulation give excellent agreement (rms error = 1.2 °C) with the measurements (Fig. 5). The variation in epilimnion temperature is simulated accurately; this is evidence that the model is simulating surface heat transfer and wind mixing in the epilimnion accurately. The most important features of the hypolimnion temperature are the rate of heating of the hypolimnion during summer and the duration of stratification. These features are simulated well. It should be noted that there are significant interannual variations in the rate of heating of the hypolimnion. The rate of heating of the hypolimnion was much greater in the high drawdown years of 1991, 1993, and 1995 than other years (Fig. 5). A feature of thermal stratification that directly affects eutrophication is the depth of the thermocline, with shallow mixed layer depth generally associated with increased algal productivity. Model predictions of the observed seasonal increase in thermocline depth from mid-summer through fall, and also short-term (e.g., weekly) fluctuations associated with meteorological events, are simulated well (rms error = 2.4 m; Fig. 6).

Routine measurements of the temperature of drinking water withdrawal are made at the upstream end of the tunnel leading from Cannonsville Reservoir (Fig. 7). Model predictions of the withdrawal temperature compare well (rms error = 1.8 °C) to the measurements (Fig. 7) for the 8 years of simulation, although there is some consistent underprediction of temperature in the spring. The prediction of withdrawal temperature indicates that the calculation of the depth range in the water column from which the intakes are drawing water is accurate, which is critical for the prediction of withdrawal water quality (Doerr et al. 1998).

As described above, the vertical position at which tributary inflow enters the reservoir water column as idealized by the multi-layer model is dependent on the relative density of the inflow and surface waters. In spring, when WBDR is warmer that the reservoir, the river enters the water column at the surface (Fig. 8). When the river inflow becomes cooler than the reservoir surface waters in June (Fig. 2b), the inflow enters the water column at or just above the thermocline, a condition which persists through the remainder of the stratification period. By late October, the inflow is plunging to the reservoir bottom. The prediction of plunging in September and October (Fig. 8) is consistent with temperature observations which detected relatively cold water at the reservoir bottom after loss of stratification (Owens 1998b).
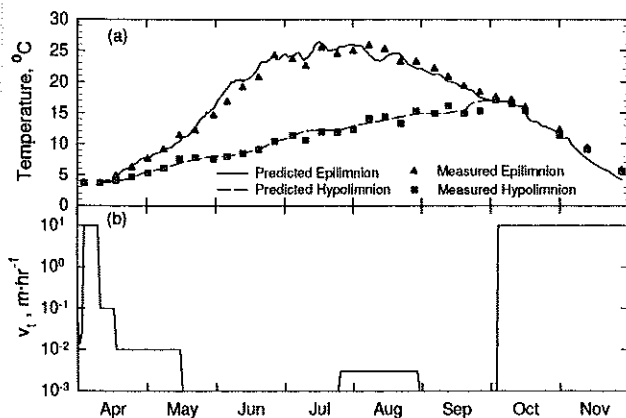

Figure 3.–Results of the application of the two-layer hydrothermal model for 1995: a) predicted temperatures (°C) and measurements determined as volume-weighted averages from measured profiles; b) variation of transfer coefficient v_t (m · hr⁻¹) determined by model calibration.
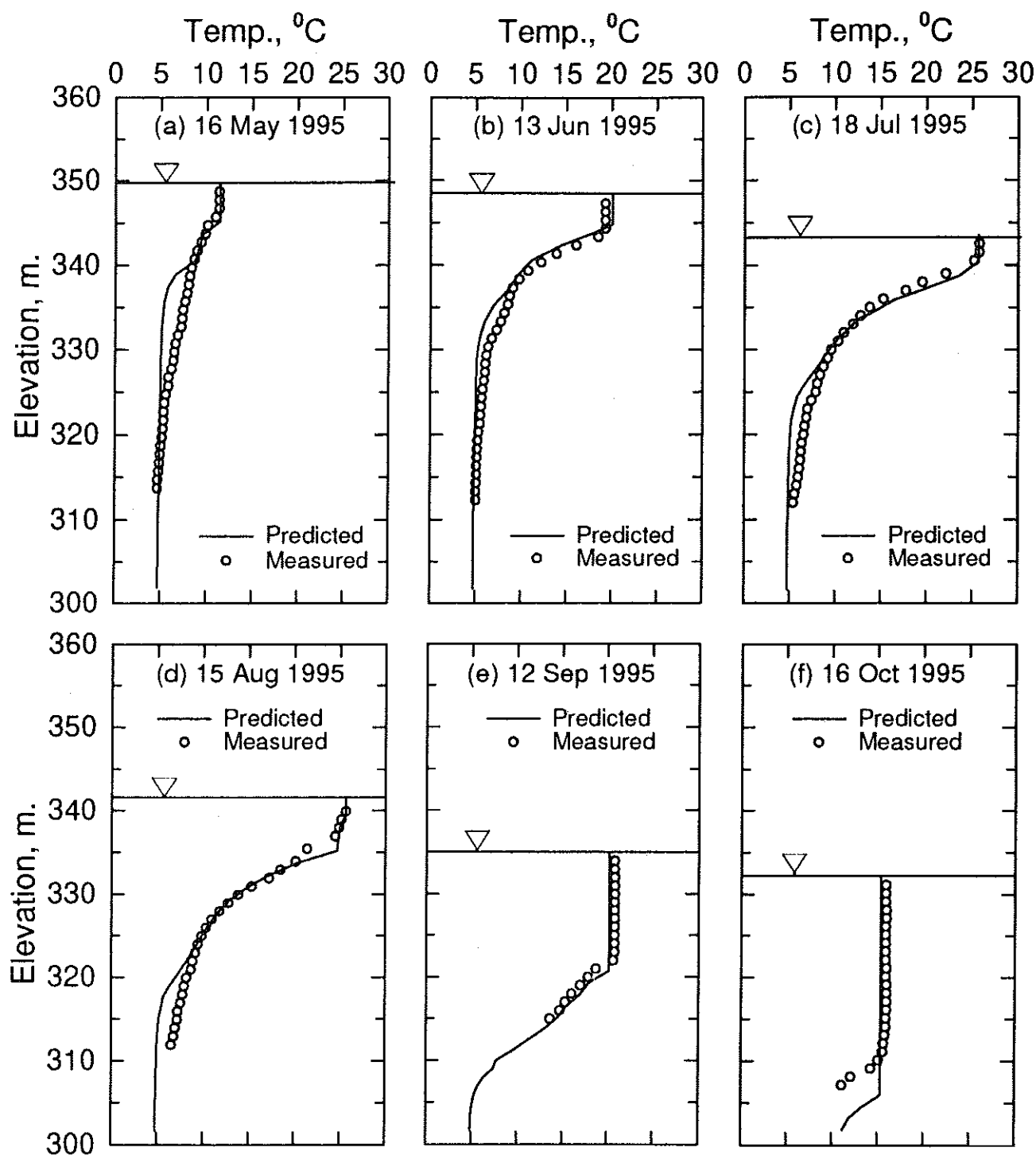
Figure 4.–Selected mid-month temperature profiles (°C) measured and predicted by the multi-layer hydrothermal model for 1995: a) 16 May; b) 13 June; c) 18 July; d) 15 August; e) 12 September; and f) 16 October.

Discussion

The primary goal of the hydrothermal model is to support analysis and prediction of eutrophication in Cannonsville Reservoir. The stratification conditions

which are known to affect eutrophication include duration of stratification, hypolimnetic temperature during stratification, and thickness of the epilimnion. The duration of stratification quantifies the time that the hypolimnion is isolated from reaeration at the water
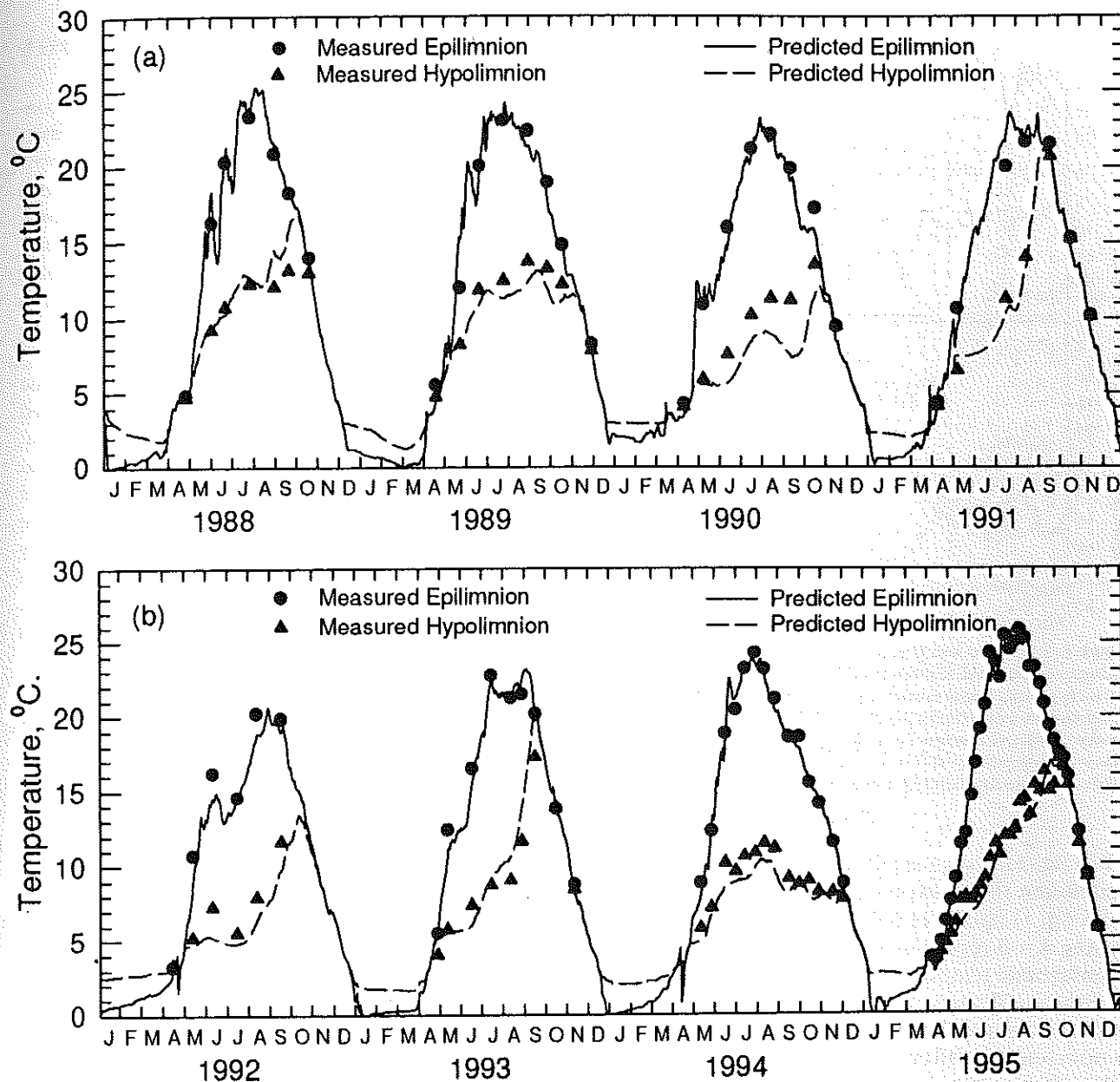
Figure 5.-Volume-weighted average temperatures (°C) for the epilimnion and hypolimnion: a) 1988-1991; b) 1992-1995. Measurements are volume-weighted averages from profiles; predictions are from a continuous 8-year simulation from the multi-layer model and are computed as volume-weighted averages from predicted profiles.

surface, so that an increase in the duration in a eutrophic reservoir may reduce dissolved oxygen in the hypolimnion. The temperature of the hypolimnion, which is likely related to the duration of stratification, affects the rate of biochemical processes in the lower waters, such as decomposition of organic material and sediment oxygen demand. Changes or variations in hypolimnetic temperature may also affect the fish population that the reservoir may support. The thickness of the epilimnion influences the magnitude of algal productivity, such that productivity increases with decreasing

epilimnion depth under nutrient-saturated, light-limited conditions. In order to summarize the predictions of the hydrothermal model in terms of possible impact on eutrophication conditions, the following three statistics are considered: duration of stratification, average summer (June through August) thermocline depth, and average August hypolimnetic temperature (volume-weighted average for the water column below the thermocline).

A sensitivity analysis to selected model inputs shows that under all historical conditions, vertical diffusion
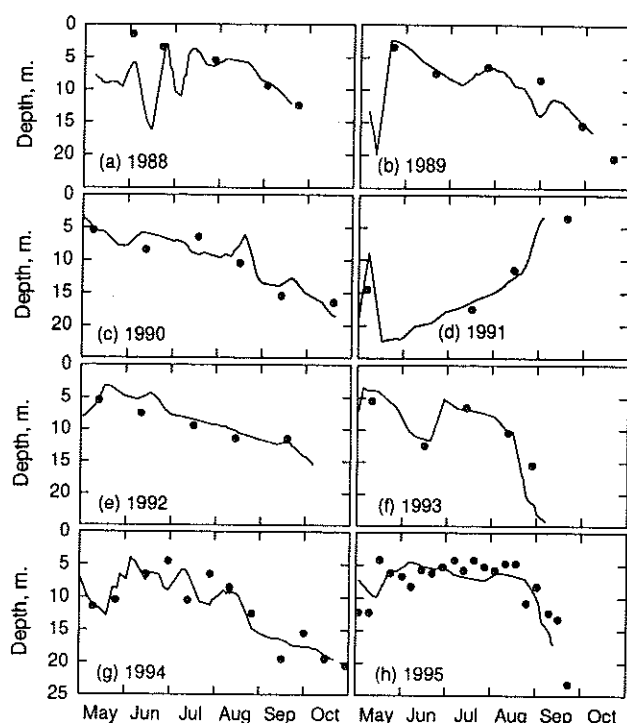
Figure 6.–Measured and predicted thermocline depth (m) for the spring to fall interval of years from 1988 through 1995. Predictions are from the multi-layer model. Thermocline depth defined as depth of maximum temperature gradient determined from temperature profile. Values of thermocline depth are shown only for conditions where a temperature difference of at least 2 °C existed for a predicted or measured temperature profile.

(K in Eq. 1) plays a small role in transport from the epilimnion to the hypolimnion relative to advection (w in Eq. 1) once thermal stratification is established. Setting $K = 0$ results in a modest underprediction of hypolimnetic temperatures in summer. This result is consistent with a simple heat budget calculation for the bottom waters of the reservoir (Owens 1998b), and is supported by other reservoir modeling studies (Harleman 1982).

The variation in predicted stratification characteristics for the historical (baseline) conditions indicate significant yearly variation (Table 3). The range of duration of stratification is 164 to 221 days, while the range of August hypolimnetic temperature is 8.3 to 13.9 °C. If inflow and outflow are "lumped" together as describing reservoir hydrology, it is of interest to determine if either year-to-year variations in hydrology or meteorology is dominant in determining the variation in predicted stratification characteristics. Various model forecasts were made by combining fixed hydrology with variable meteorology, and also fixed meteorology with variable hydrology. The results indicate that hydrology, comprised of both natural inflow conditions and controllable reservoir outflows, has a greater impact on variability in stratification characteristics than meteorology.

Management Considerations

In addition to meteorologic and hydrologic conditions, the stratification and transport characteristics of Cannonsville Reservoir are affected by reservoir operation. Reservoir managers have the ability to control the rate of dam release and drinking water withdrawal, and thus water storage in the reservoir. One of three intake locations may be used for the drinking water withdrawal. The hydrothermal model may be used to study the effect of modification of these outflows on stratification and transport characteristics.

Operators may choose to withdraw water from one of three intakes in the Cannonsville Reservoir located over a range of elevation (Table 1). Practice in recent years has been to use the middle intake at all times that the reservoir level is above this intake. The low level intake is used otherwise, which occurred 11% of the time during the period 1988 through 1995. To study the affect of modifying the intake elevation on stratification characteristics, the continuous simulation of actual historical conditions for the period 1988 through 1995 was used as a baseline simulation. Additional simulations using the low intake continuously and using the highest active intake for the entire 8-year simulation were run. The highest active intake was assumed to be highest of the three intakes that is at any given time at least 2 meters below the current reservoir level. As only the location, but not the rate, of withdrawal was modified, the variation of reservoir level (storage) was identical to historical conditions in these simulations. The average duration of stratification and thermocline depth determined from the 8 years of simulation are only slightly sensitive to the selected intake depth (Table 4), while the average August hypolimnetic temperature is more sensitive. The changes in these characteristics for individual

Table 3.–Hindcast stratification characteristics predicted by the multi-layer model for historical conditions.

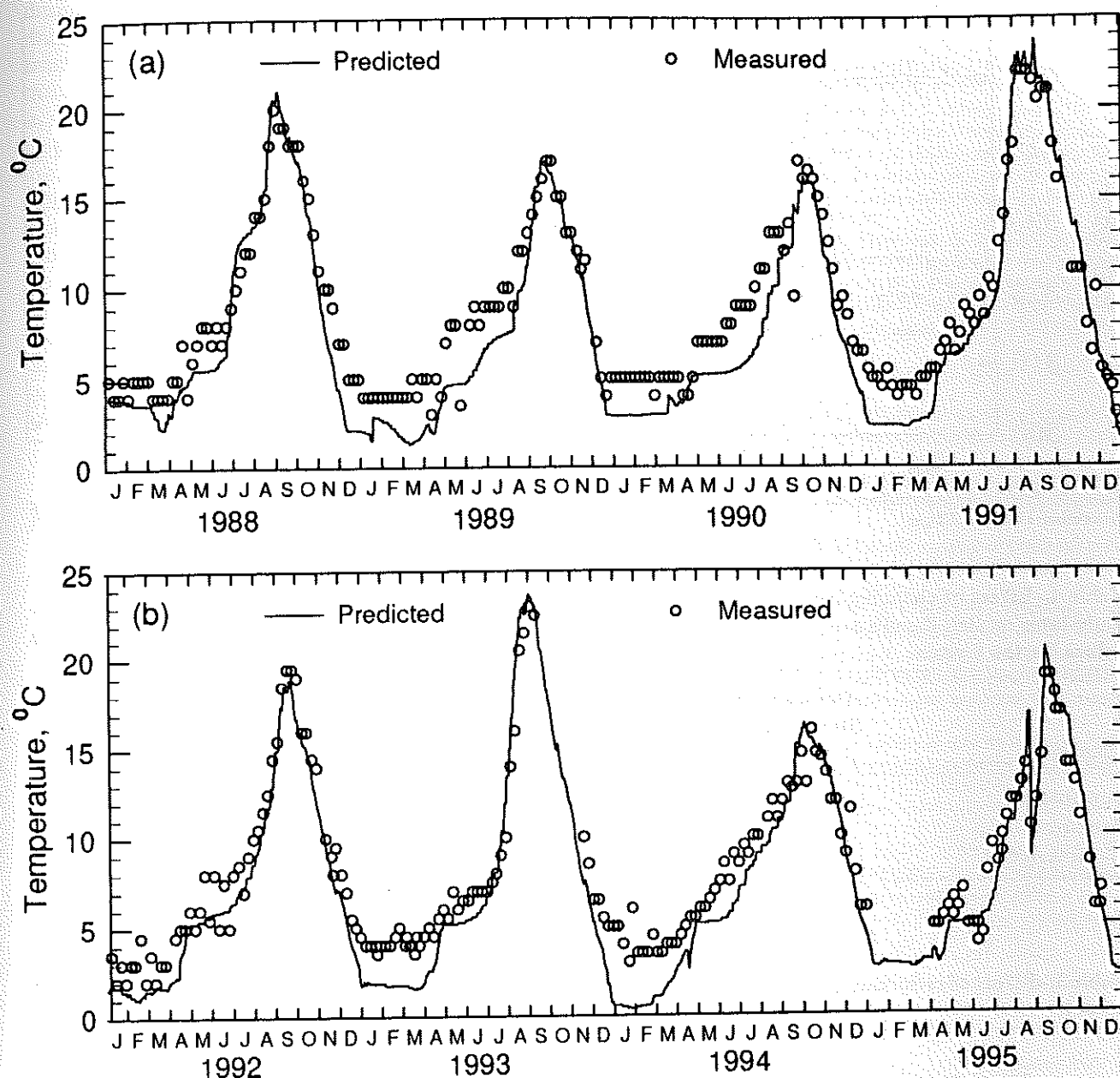| Year	Duration of Stratification (days)	Thermocline Depth (m)	August Hypolimnetic Temperature (°C)
1988	171	7.7	13.9
1989	195	7.7	10.7
1990	207	9.5	8.3
1991	164	9.8	13.0
1992	198	8.3	9.2
1993	172	10.2	12.8
1994	221	9.4	9.4
1995	181	6.7	11.8
Mean	188	8.1	11.1

Figure 7.–Measured and predicted drinking water withdrawal temperatures (°C) at the entrance to the tunnel leading to Rondout Reservoir.

years are represented well by the mean values.

Reservoir managers also control the rate of release to the WBDR downstream of the dam. As in the case of withdrawals, the release from Cannonsville must consider operations in other reservoirs. In particular, the cumulative release from Cannonsville, Pepacton, and Neversink Reservoirs must meet a value prescribed by the Delaware River Basin Commission during low flow conditions. Thus, any adjustment to the release from Cannonsville must consider the simultaneous releases from Pepacton and Neversink.

The effect of the rate of dam release on stratification was studied using the 8-year meteorologic and reservoir

inflow conditions, with emphasis on 1991, the year with the lowest average inflow and greatest drawdown. Simulations were made for the actual historical conditions, and for reduced rates of release. Reductions of dam release of 25, 50, 75, and 100% (no release) on a continuous basis over the entire year from the actual releases were considered. In these simulations, historical reservoir inflows were used, and the spillway flow was modified using a rating curve to account for the increase in reservoir storage associated with the decrease in release. The results indicate that, on average, reduction in dam release has a moderate effect on stratification characteristics (Table 5). However, during the large
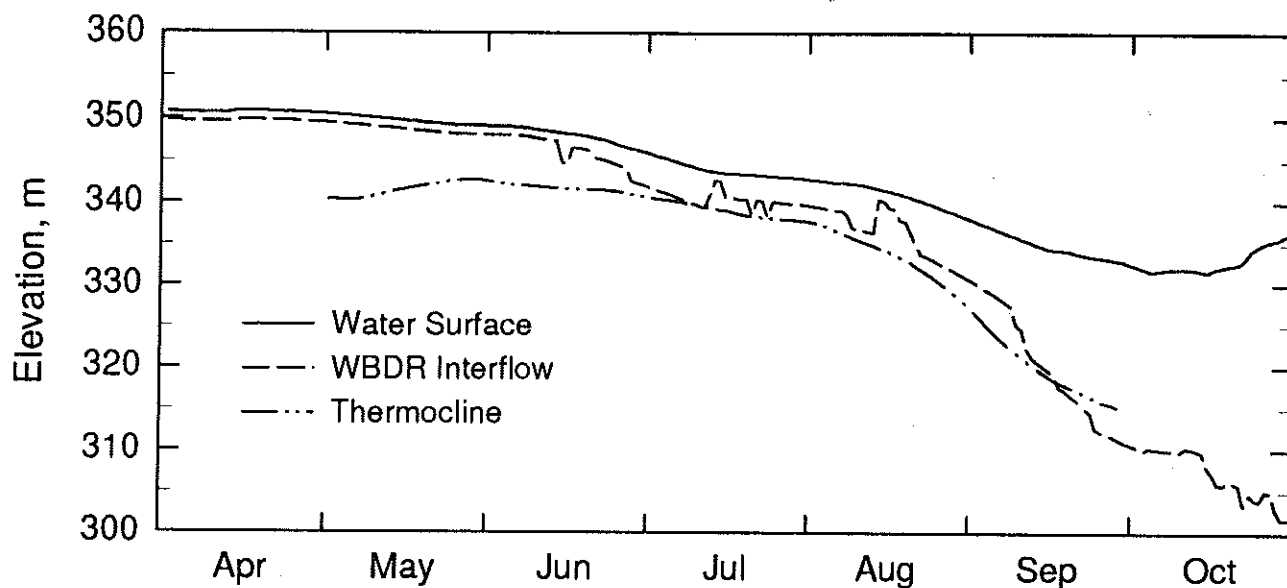
Figure 8.–Predicted water surface elevation, West Branch Delaware River interflow elevation, and thermocline elevation for April through November 1995 (NGVD, m).

Table 4.–Effect of changing intake locations on selected stratification different characteristics predicted by the multi-layer model. Results are from a continuous simulation for 1988-1995, and characteristics shown are mean values for the 8 years.

Condition	Duration of Stratification (days)	Thermocline Depth (m)	August Hypolimnetic Temperature (°C)
Low Intake	185	9.0	11.4
Baseline	188	8.1	11.1
Highest Active	190	8.2	9.7

Table 5.–Effect of reduction of dam releases on selected stratification characteristics predicted by the multi-layer model.

Reduction in Release (%)	Duration of Stratification (days)	Thermocline Depth (m)	August Hypolimnetic Temperature (°C)
Average for 8-year simulation:			
0	188	8.6	11.1
25	193	8.4	10.6
50	196	8.2	10.4
75	199	8.1	10.1
100	201	8.0	9.7
1991 simulation:			
0	164	9.8	13.0
25	195	9.8	11.6
50	212	8.9	10.0
75	214	7.9	9.4
100	215	6.6	9.3

drawdown year of 1991, the effect was much more dramatic. Reductions in dam release of 25 and 50% from historical values resulted in increases in the duration of stratification of 24 and 41 days, and decrease in August hypolimnetic temperature of 1.4 and 3.0 °C, respectively. The changes in duration of stratification are largely associated with the timing of fall turnover, rather than the onset of stratification in spring. Stratification characteristics are more sensitive to modifications in dam release than to drinking water withdrawal because the dam release draws water from the deepest part of the basin, which contains the coldest water in the reservoir. The release of such cold water allows the combined action of wind mixing and cooling of the surface waters to enhance heat transport to the lower waters, which encourages the occurence of fall turnover.

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