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Thermal and Heat Transfer Characteristics of Cannonsville Reservoir

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ABSTRACT

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Observations of the spatial and temporal distribution of temperature in Cannonsville Reservoir over the 1988-1995 period are reviewed, with emphasis on 1994 and 1995. The dominant spatial variations in temperature are in the vertical direction (thermal stratification), with modest spatial variations along the longitudinal axes of the basin. Longitudinal temperature variations were greatest in the spring, with shallow, upstream waters being warmer than at deeper sites downstream near the dam. Diurnal temperature variations of the surface waters of the reservoir were generally less than 2 °C. The variations of temperature of two major reservoir tributaries are also documented. The tributaries are generally warmer than reservoir surface waters in spring, but are cooler through most of the summer and the fall. Diurnal fluctuations in tributary temperature may be significant, with day-night changes as large as 15 °C observed for Trout Creek. A reservoir heat budget calculation for 1995 indicates that inflow/outflow and water surface heat transfer are both important in affecting temperature variations of the reservoir. Direct measurements of incident solar radiation at the reservoir site for a single year allowed calibration of a predictive relationship that may be used in hydrothermal modeling. Estimation of empirical coefficients in predictive expressions for other components of water surface heat transfer was performed using the net water surface heat transfer computed from the heat budget. The implications of these findings for predictive hydrothermal modeling of the reservoir are discussed.

Key Words: thermal stratification, surface heat transfer, hydrothermal models.

Hydrothermal models of lakes and reservoirs describe the temporal and spatial variations of temperature, water motion, and mixing in a water body in response to external forcing conditions (Harleman 1982). These forcing conditions include natural meteorologic and hydrologic conditions, and in the case of reservoirs, operation of outlet works. Hydrothermal models are based on budget calculations for water and heat, and in some cases other quantities such as momentum (Blumberg 1986). The heat budget calculations typically consider the major sources and sinks of heat, these being water surface heat transfer and inflow/outflow (Ragotzkie 1978).

This paper describes the analysis of monitoring data from Cannonsville Reservoir which was gathered to provide general guidance and detailed quantitative information for the application of hydrothermal and water quality models to the reservoir. The observed spatial distribution of temperature in the reservoir is an important factor in determining the type of (one, two, or three dimensional) hydrothermal model which should be used (Orlob 1983, Martin 1988). This review, together with observations of the spatial variation in water quality characteristics of interest (Kennedy et al. 1982), serves as the basis for selection of a model appropriate to address water quantity and quality questions.

The contribution of inflow and outflow to a reservoir heat budget is determined by the flow rate and temperature of individual water flows (Ragotzkie 1978, Johnson and Merritt 1979). The flow rate of major reservoir inflows and outflows are often measured continuously, while temperature measurements may be made less frequently. Surface heat transfer has several component processes, these being short and long wave radiation, evaporation, and conduction, many of which are difficult to directly measure. To support the development of hydrothermal models for the reservoir (Owens 1998a, Gelda et al. 1998), two analyses associated with the heating/cooling of the reservoirs by inflow/outflow and surface heat transfer were performed. First, an empirical model was developed to provide estimates of tributary stream temperature on days when measurements were not made. These temperature estimates are expected to improve the accuracy of heat budget calculations and of buoyancy-related mixing calculations performed by hydrothermal models. Second, a reservoir-wide heat budget for the spring-fall period of 1995 was calculated, which allowed the net water surface heat transfer to be identified and compared to heating and cooling due to inflow/outflow. Together with observations of meteorological conditions and water surface temperature, the estimated surface heat flux was used to identify the value of coefficients used in predictive expressions for two components of surface heat flux.

Cannonsville Reservoir is a drinking water supply and downstream flow augmentation impoundment owned and operated by New York City Department of Environmental Protection. The reservoir has mean and maximum depths of 19 and 50 m, respectively, at full capacity, and receives inflow from a 1160 km^2 watershed. Two major tributaries, the West Branch of the Delaware River (WBDR) and Trout Creek (TC) enter the two "arms" of the basin and drain 79% and 5% of the watershed area (Fig. 1). Reservoir outflow occurs in three forms: over a spillway located adjacent to the dam, through release ports located at the base of the dam, or through one of three drinking water intake structures (Fig. 1). Cannonsville Reservoir has been classified as eutrophic, and is the focus of monitoring and modeling studies aimed at managing and improving reservoir water quality.

Methods

The temperature monitoring program for the reservoir was designed to capture the three-dimensional (vertical, longitudinal, and lateral) variations in temperature over time. Temperature profiles were measured at six sites (Fig. 1) on 14 dates from 9 May through 30 November 1994, and on 37 dates from 4 April through 28 November 1995. Temperature profiles were made roughly once per month from April through October during 1988-93. Additional profiles were measured along lateral transects on several dates in 1995, with five profiles measured over the basin width at sites 1, 2 and 4, and three profiles measured at sites 3, 5 and 6. The depth interval for temperature profile measurements was 0.5 m in 1995, and 1.0 m in earlier years. Additionally, temperature sensors with an hourly recording frequency were deployed at sites 1 and 4 (Fig. 1) for portions of the 1995 monitoring period, allowing the diurnal variation of surface water temperature to be identified.

In order to condense the temperature profile measurements, volume-weighted average temperatures were computed for both the entire reservoir water volume and the epilimnion and hypolimnion volumes.

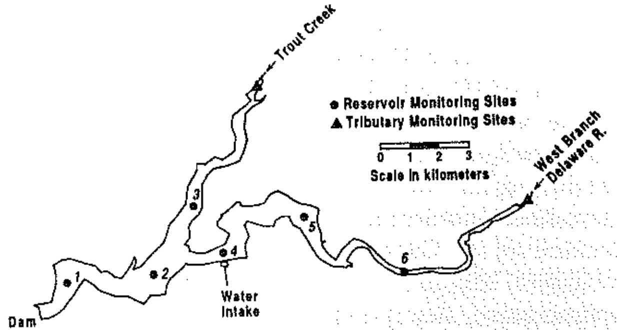

Figure 1.–Base map of Cannonsville Reservoir showing location of dam and drinking water intakes, major tributaries, reservoir monitoring sites, and tributary monitoring sites.

The average temperature T_A for the entire reservoir was computed by

$$T_A = \frac{1}{V_T} \Sigma T_i \Delta V_i \tag{1}$$

where T_i is an individual temperature measurement, ΔV_i is the volume of water associated with that measurement, and V_T is the total reservoir volume. Thus, this calculation involved the discretization of the total reservoir into a number of volume increments, and accounted for temperature variations in the vertical and longitudinal directions. In addition, the total reservoir volume was divided into upper (epilimnion) and lower (hypolimnion) layers, separated by the thermocline, assumed to be located at the maximum vertical temperature gradient using temperature profile data from site 1. Volume-weighted average temperatures for the epilimnion (T_E) and hypolimnion (T_H) were computed by

$$\begin{aligned} T_E &= \frac{1}{V_E} \sum_{z_i > z_t} T_i \Delta V_i \\ T_H &= \frac{1}{V_H} \sum_{z_i < z_t} T_i \Delta V_i \end{aligned} \tag{2}$$

where z_i is the elevation of the volume increment ΔV_i, z_t is the elevation of the thermocline, and V_E and V_H are the volume of the epilimnion and hypolimnion, respectively.

The temperature of the major tributaries to the reservoir (WBDR and TC) has been routinely measured. Single daytime temperature measurements were made on each stream on 25 dates in 1994 and 24 dates in 1995. In addition, temperature sensors were deployed at these two tributaries during 1995, recording the temperature at an hourly frequency on 93 days for WBDR, and 119 days for TC.

Reservoir water surface elevation and rates of the various forms of outflow from the reservoir are monitored by NYCDEP. The temperature of drinking water withdrawal was measured weekly. Streamflow of WBDR is measured by the US Geological Survey, and the flow of TC and of the remaining minor tributaries to the reservoir has been estimated from a reservoir water budget for recent years (Owens et al. 1998). Beginning in November 1994, meteorological data have been monitored at an hourly interval at a site located on the Cannonsville Dam (Fig. 1). Measured variables include wind speed and direction, air temperature, dew point temperature, and incident solar radiation. In addition, meteorological data from the National Weather Service station at Binghamton, New York, were also used in describing conditions prior to the installation of the on-site station.

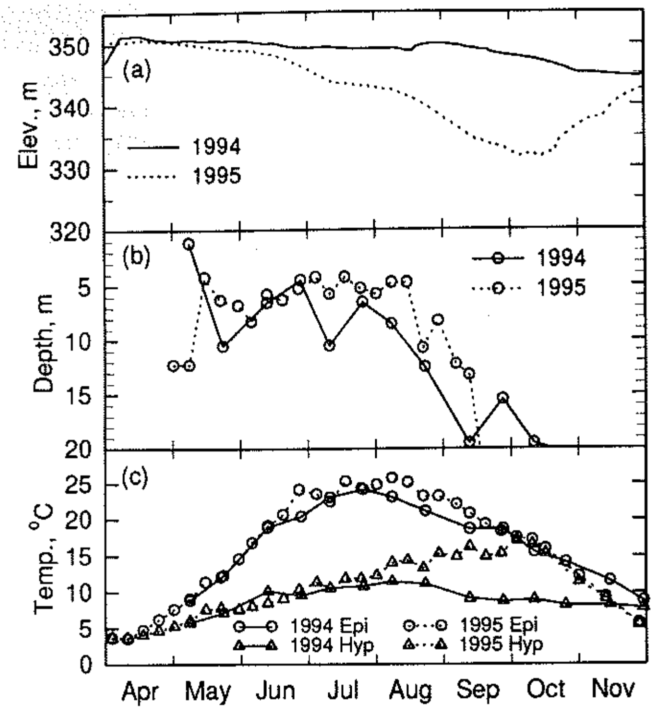

Figure 3.–Reservoir and thermal stratification characteristics for 1994 and 1995: (a) reservoir water surface elevation; (b) thermocline depth; (c) average temperature of the epilimnion (T_E) and hypolimnion (T_H).

Results

Thermal Stratification

The seasonal progression of temperature profiles at site 1 indicates a typical pattern for a dimictic reservoir (Fig. 2). Features of thermal stratification include warming of the surface waters from spring until late summer, with subsequent cooling of surface waters and deepening of the epilimnion thereafter. Progressive warming of the hypolimnion occurs throughout the period of stratification. The most significant difference in the temperature profiles for 1994 and 1995 is that thermal stratification persisted later in the fall in 1994 compared to 1995 (Fig. 2). The earlier fall turnover in 1995 may be related to the large drawdown of the reservoir relative to 1994 (Fig. 3a).

An important feature of thermal stratification is the depth of the thermocline, which is assumed to be located at the maximum vertical temperature gradient. Thermocline depth during early summer was similar for 1994 and 1995, while the thermocline was generally deeper in July and August of 1994 by roughly 3 m relative to 1995 (Fig. 3b). The seasonal variation of average temperatures for the epilimnion and hypolimnion determined from Eq. 2 clearly depicts the significantly longer duration of summer stratification in 1994 relative to 1995 (Fig. 3c), indicating a potential linkage between reservoir drawdown (Fig. 3a) and thermal stratification. Analysis of paired observations of average summer (June through August) reservoir elevation and maximum hypolimnetic temperature (T_H, Eq. 2) for the period 1988 through 1995 indicates an inverse relationship (Fig. 4).

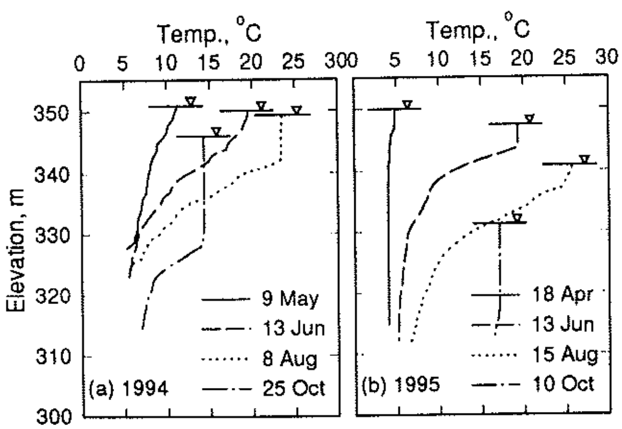

Figure 2.–Selected observed temperature profiles from site 1 of Cannonsville Reservoir: (a) 1994; and (b) 1995.

While strong vertical variations in temperature were observed, the longitudinal temperature variations were more modest. The seasonal variation in temperature observed during routine weekly monitoring in 1995 at stations extending from the Cannonsville Dam through the WBDR arm at fixed depth (Fig. 5) shows longitudinal variations that may be as large as 5 °C, but average less than 1 °C over the season. Longitudinal temperature variations are greatest at the surface, with up-reservoir temperatures generally higher than those near the dam (Fig. 5a). Diurnal temperature measurements from sites 1 and 4 at a depth of 0.5 m indicate that the greatest longitudinal temperature variation is in the spring (Fig. 6a), with

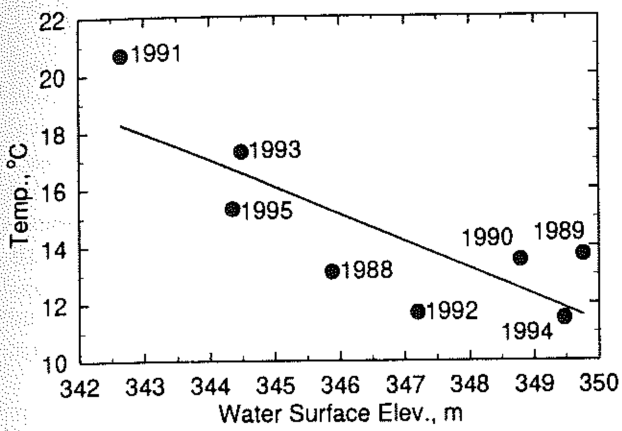

Figure 4.–Relationship between maximum hypolimnetic temperature (T_H) and average summer (June through August) reservoir elevation for the 8-year period 1988 through 1995.

site 4 being consistently warmer than site 1. In summer and early fall, the diurnal observations indicate very similar temperatures near the surface at sites 1 and 4 (Fig. 6b and 6c). The temperature measurements along lateral transects indicate that there are no significant temperature variations in the lateral directions.

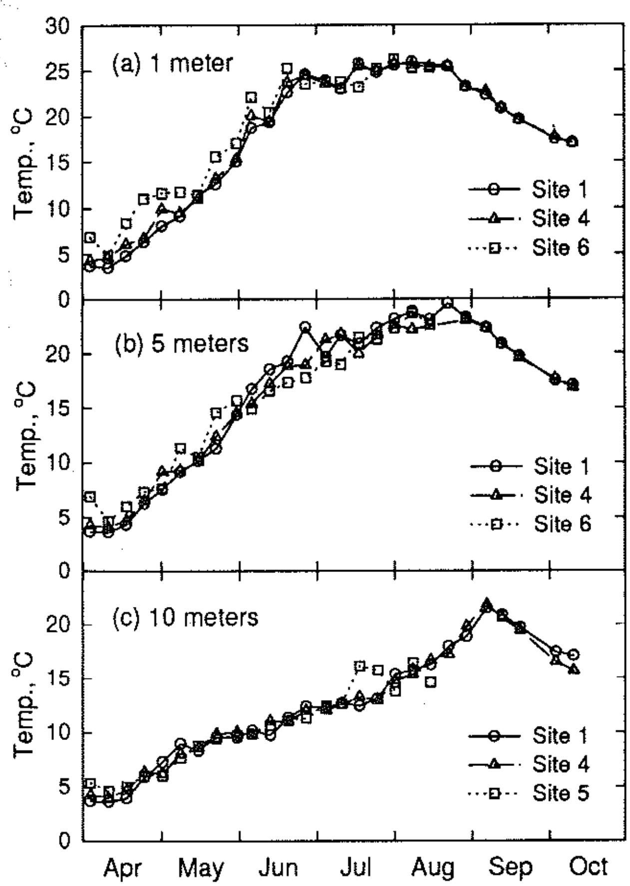

Figure 5.–Seasonal variation of water temperature at a fixed depth at 3 sites over the length of Cannonsville Reservoir during 1995: (a) at 1 m depth, sites 1, 4 and 6: (b) at 5 m depth, sites 1, 4 and 6; (c) at 10 m depth, sites 1, 4 and 5.

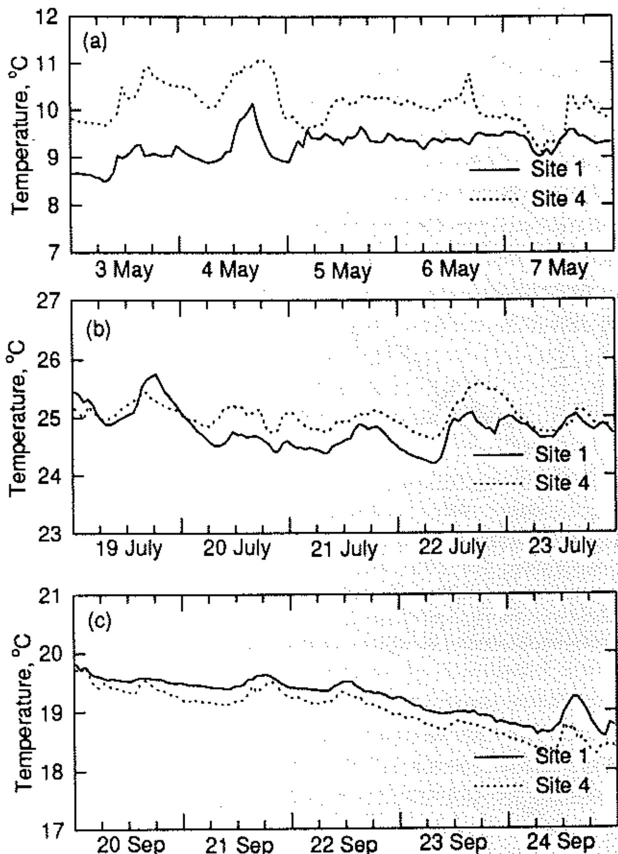

Figure 6.–Diurnal variation of temperature near the surface (depth 0.5 m) of Cannonsville Reservoir for selected 5-day periods during 1995: (a) 3-7 May; (b) 19-23 July; and (c) 20-24 September.

Tributary Temperature: Observations and Prediction

A distinct seasonal pattern in the relative temperature of the tributaries and reservoir surface waters was observed both in 1994 and 1995. The temperatures of the WBDR and TC were warmer than reservoir surface waters from spring through early summer, but cooler from mid-summer through fall (Fig. 7). In addition, TC was consistently cooler than WBDR throughout the monitoring period. Diurnal observations of tributary and reservoir surface water temperature indicate the same general trend, and also indicate that the stream, and particularly the smaller TC, show significant diurnal temperature variation (Fig. 8); in late May 1995, the TC temperature varied by as much as 15 °C over a 12-hr period (Fig. 8a).

While the temperatures of WBDR and TC were effectively monitored on a continuous basis for portions of 1995, there are gaps in these measurements. In addition, the frequency of measurements in previous years was much lower, in some cases monthly during

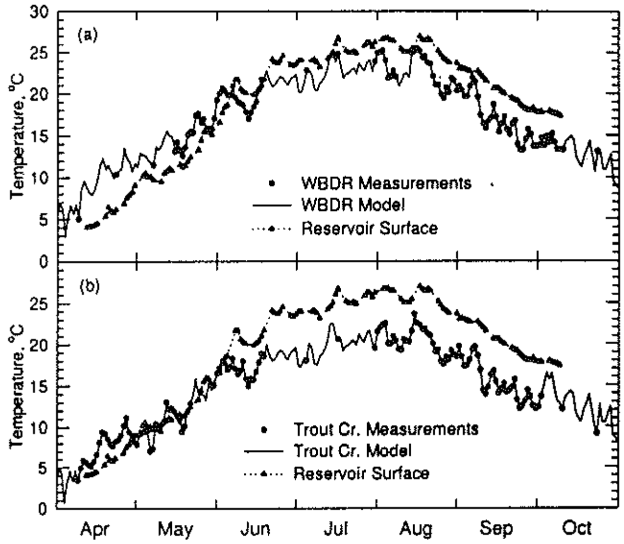

Figure 7.–Observations and predictions of tributary water temperature for 1995 compared to reservoir water surface temperature: (a) West Branch Delaware River; (b) Trout Creek. Observations represent single measurements or daily average of hourly measurements, while model predictions are daily averages.

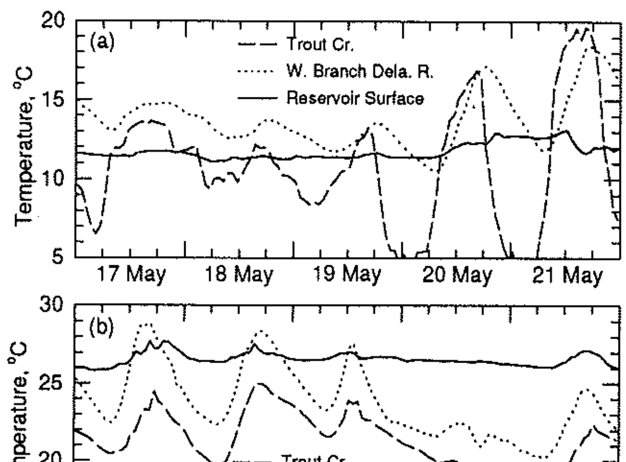

Figure 8.–Diurnal variation of water temperature of West Branch Delaware River, Trout Creek, and reservoir water surface (0.5 m depth, site 4) for selected 5-day periods during 1995: (a) 17-21 May; (b) 2-6 August; and (c) 26-30 September.

the warmer months. Due to the dependence of the reservoir heat budget on inflow temperature (Johnson and Merritt 1979) and of transport and mixing processes on the relative temperature of streams and reservoir waters (Alavian et al. 1992, Owens 1998b), an empirical model was developed to estimate daily average stream temperatures on days that measurements were not made. In addition to stream temperature measurements, this model requires daily measurements of air temperature.

This empirical model begins by fitting a seasonal harmonic function to the observed stream temperatures. This function is

$$T = \overline{T} + \Delta T \cos\left(\frac{2\pi}{N_D}(J - J_M)\right) \quad (3)$$

where $\overline{T}$ is the average temperature over the year, ΔT is the amplitude of the annual variation, N_D is the number of days in the year, J is the julian day, and J_M is the julian day on which the maximum temperature occurs. The values of the coefficients $\overline{T}$, ΔT, and J_M are determined by minimizing the root mean square error between the estimated and the observed temperature. This process was repeated separately for WBDR and TC using the observations from 1 year. Also, a separate function of the form of Eq. 3 was applied to the observed daily air temperatures from the same year. The functions so determined for 1995 indicate that the average air temperature over the year is lower than for tributaries, and air temperature has greater seasonal variation (Fig. 9a and 9b).

For each day on which a tributary temperature measurement was made, an error or residual equal to the difference between the estimate from Eq. 3 and the measurement may be computed. A similar residual between the measured and predicted air temperature was also determined. The empirical model is based on the assumption that there is a linear relationship between the residual in the predicted tributary temperature and the residual in the predicted air temperature on the same day. In other words, it is assumed that if the air temperature is warmer than average (specifically warmer than predicted by Eq. 3), then the tributary temperature will also be warmer than average. The relationship between water and air temperature residuals for WBDR (Fig. 9c) and TC (Fig. 9d) indicates that a reasonable relationship exists, and that water temperature residuals are about half of corresponding air temperature residuals. Thus, on days that a tributary measurement is not available, an estimate is computed as follows. The residual air temperature is computed as the difference between the measured value and that predicted by Eq. 3. A corresponding tributary temperature residual is computed from the linear relationship (Fig. 9c, 9d).

The resulting tributary temperature residual is then added to the seasonal value predicted by Eq. 3 to yield final predictions (Fig. 7).

Heat Budget Analysis

Neglecting heat transfer between the water and underlying sediments, a heat budget for the reservoir water volume may be written as

$$\rho c \frac{d}{dt}(V_T T_A) = \Phi_{IO} + \Phi_S \qquad (4)$$

where ρ and c are the density and specific heat of water, and Φ_O is the net rate of heating due to inflow and outflow, and Φ_S is the net rate of heating due to water surface heat transfer. The rate Φ_{IO} may be defined as

$$\Phi_{IO} = \rho c(Q_W T_W + Q_T T_T + Q_M T_M - Q_S T_S - Q_R T_R - Q_D T_D) \qquad (5)$$

where Q and T represent volumetric flow rates and temperatures, with the subscripts W, T, and M referring to WBDR, TC, and minor inflow, and subscripts S, R,

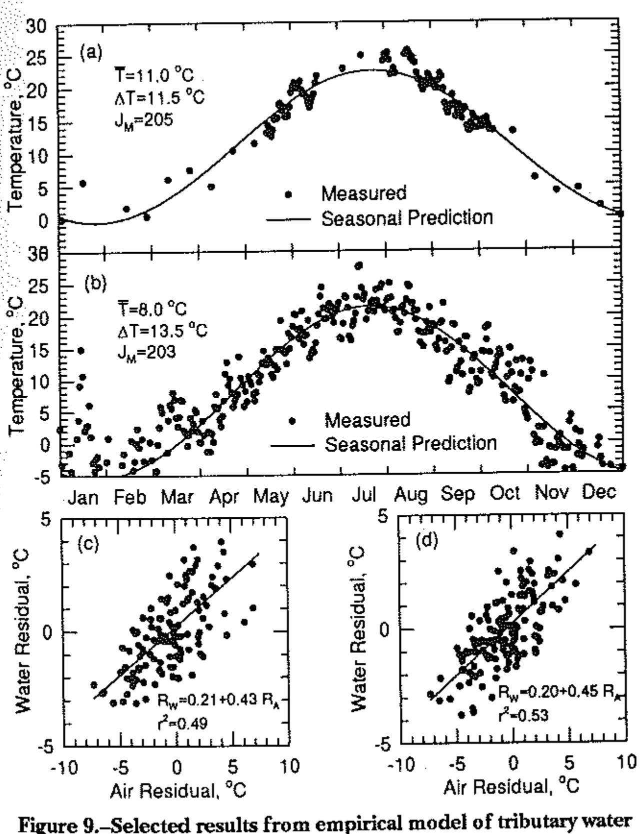

Figure 9.–Selected results from empirical model of tributary water temperature for Cannonsville Reservoir in 1995: (a) temperature measurements of WBDR and best-fit sinusoidal function; (b) air temperature measurements and best-fit sinusoidal function; (c) paired values of water temperature and air temperature residual (error) for WBDR, with resulting linear regression equation; and (d) paired values of water temperature and air temperature residual (error) for TC, with resulting linear regression equation.

and D referring to spillway, dam release, and drinking water outflow, respectively. The rate due to surface transfer is defined by $\Phi_S = \phi_N A_S$, where ϕ_N is the net surface heat flux, and A_S is the surface area of the reservoir.

It is desirable to use the heat budget expressed by Eq. 4 and measurements of reservoir temperature and bathymetry, inflow and outflow rates, and temperatures to estimate the surface heat flux ϕ_N over the monitoring period. If Eq. 4 is integrated over the time interval between consecutive days on which measurements of T_A (Eq. 1) were made, the average surface heat flux $\overline{\phi_N}$ for the time interval is given by

$$\overline{\phi_N} = \frac{1}{\overline{A_S}}\left[\rho c \frac{(V_T T_A)^{j+1} - (V_T T_A)^j}{\Delta t} - \overline{\Phi_{IO}}\right] \qquad (6)$$

where the superscript j+1 refers to values at the end of the time interval Δt, while those with the superscript j refer to values at the beginning of the time interval, and the quantities $\overline{A_s}$ and $\overline{\Phi_{IO}}$ refer to average values of the reservoir surface area and heat transfer due to inflow/outflow over the time interval. In calculations with Eq. 6, inflow temperatures as estimated above were used, with the temperature of minor tributaries assumed to be equal to TC. Measurements were used to determine the temperature of outflows, with linear interpolation used between measurements of these relatively slowly-varying quantities.

The seasonal variation of T_A (Eq. 1) for 1995 shows the expected pattern, with maximum temperature, and thus heat content, occurring in late summer (Fig. 10a). Flow-weighted average inflow (T_{IA}) and outflow (T_{OA}) temperatures, computed using the following expressions

$$T_{IA} = \frac{Q_W T_W + Q_T T_T + Q_M T_M}{Q_W + Q_T + Q_M} \qquad (7)$$
$$T_{OA} = \frac{Q_S T_S + Q_R T_R + Q_D T_D}{Q_S + Q_R + Q_D}$$

indicate that on average inflow is warmer than the reservoir through August 1995, and was cooler thereafter (Fig. 10a). Due to releases from the deepest part of the reservoir, the average outflow temperature is less than the reservoir average throughout the stratification period (Fig. 10a).

The variation of the net surface heat flux computed from the reservoir heat budget (Eq. 6) shows the expected seasonal variation of positive ϕ_N during spring and early summer, and negative ϕ_N in late summer and fall (Fig. 10b), with higher frequency fluctuations associated with meteorological variations. Comparison of the relative magnitudes of heating associated with surface heat transfer (Φ_S) and with inflow/outflow (Φ_{IO}) during 1995 (Fig. 10c) indicates that the two are of the

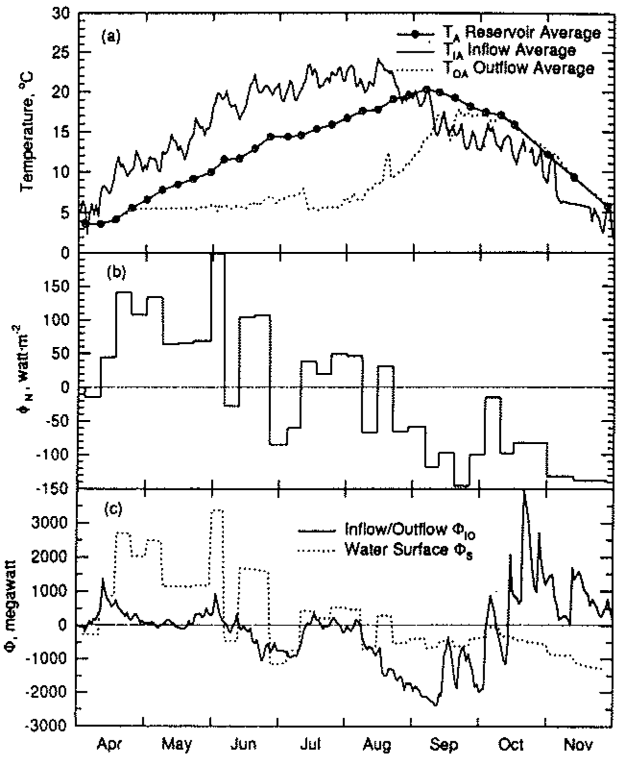

Figure 10.–Results of Cannonsville Reservoir heat budget analysis for 1994 and 1995: (a) average reservoir temperature (T_A) and flow-weighted average inflow (T_{IA}) and outflow (T_{OA}) temperatures; (b) variation of surface heat flux f_N determined from reservoir heat balance calculation; (c) rate of heating associated with surface transfer (Φ_N) and inflow/outflow (Φ_{IO}).

same order of magnitude, with surface heating being larger in the spring, and inflow/outflow dominating in late summer and fall, particularly during the runoff events of late October.

Estimation of Surface Heat Transfer Coefficients

While determination of the water surface heat flux for historical periods may be conducted as described above, management models of the reservoir require that a predictive expression for the surface heat flux ϕ_N be developed so that hypothetical future conditions may be simulated. In hydrothermal models of Cannonsville Reservoir (Owens 1998a; Gelda et al. 1998), predictive expressions for the components of the net water surface heat flux ϕ_N that consider meteorological conditions and water surface temperature are used. These predictive surface heat flux models contain coefficients whose value for a particular water body is not known precisely. The variation of the net surface heat flux as determined above was used together with water surface temperature and on-site meteorological measurements to determine site-specific values for heat flux coefficients.

The surface heat flux is expressed as the summation of five individual components (Edinger et al. 1968, Henderson-Sellers 1984) as

$$\phi_N = \phi_{SN} + \phi_{AN} + \phi_B + \phi_E + \phi_C \tag{8}$$

where the terms on the right side of Eq. 8 represent net (incident less reflected) solar (short wave) radiation, net atmospheric (long wave) radiation, back radiation from the water surface, evaporative heat loss, and conduction. Predictive expressions for the individual components are as follows. The net solar radiation is computed by

$$\phi_{SN} = \phi_{SC} \sin \alpha F_A F_C F_R \tag{9}$$

where ϕ_{SC} is the solar radiation at the outer boundary of the atmosphere (1374 watt·m^{-2}), α is the solar angle, and F_A, F_C and F_R are reduction factors (≤ 1) associated with the adsorption and scattering in the atmosphere, similar reductions associated with clouds, and reflection from the water surface, respectively. The empirical atmospheric reduction factor is given by

$$(F_A = \exp\left[-\frac{T_N}{\sin \alpha}(0.128 + 0.054 \log(\sin \alpha))\right] \tag{10}$$

where T_N is the atmospheric turbidity (Henderson-Sellers 1984). The empirical cloud reduction factor is given by

$$F_C = (1 - 0.65 C^2) \tag{11}$$

where C is the cloud cover fraction ($0 \leq C \leq 1$). The reflection of incident solar radiation at the water surface is strongly related to the solar angle α. A power function relationship is used in the model as given by

$$F_R = r_1 \alpha^{r2} \tag{12}$$

where r_1 and r_2 are empirical coefficients (Eagleson 1970). The solar angle α is computed as a function of latitude, longitude, date, and time of day.

The only component of ϕ_N that has been directly measured at or nearby the reservoir site is solar radiation, beginning in November 1994. Solar radiation is distinct from the other components of surface heat transfer in that it can penetrate the water surface and directly heat water at depth, while other forms of transfer occur directly at the water surface. In addition, solar radiation penetrating the water surface also affects algal photosynthesis, and is considered in water quality models (Doerr et al. 1998). When considering the historical conditions of 1995, the direct measurements of solar radiation may be used in place of predictions (Eq. 9). The application of Eq. 9 for other periods requires that the empirical atmospheric turbidity coefficient T_N be specified. Using observations of the cloud cover C (Eq. 11) from Binghamton, the value of T_N for the Cannonsville site was determined by minimizing the error between measurements and predictions using hourly values of α and C and F_R=1 (Fig. 11a). The resulting value (T_N=2.2; rms error = 17 watt · m^{-2}) may be used in such predictions.

The general expression for long wave radiation is given by $\varepsilon\sigma T^4$, where ε is the emissivity, σ is the Stefan-Boltzmann constant, and T is the absolute temperature of the emitting mass. The empirical expression for the emissivity of the atmosphere (Swinbank 1963) assumes it to be a function of the air temperature and cloud cover as given by

$$\varepsilon_A=9.07 \times 10^{-6}\, T_A^2\, (1+.17C^2) \tag{13}$$

where T_A is the (absolute) air temperature. This expression yields the result that ε_A=0.78 for a clear sky at 20 °C. For back radiation, the water surface is assumed to have a constant emissivity of 0.97.

The evaporative heat loss is given by

$$\phi_A = \frac{L}{RT_A}\,(a + bW)\,(e_S - e_A) \tag{14}$$

where L is the latent heat of vaporization, R is the gas constant, T_A is the absolute air temperature, a and b are empirical coefficients, e_S is the saturated vapor pressure of the air at the temperature of the water surface, and e_A is the actual vapor pressure of the atmosphere. The conductive heat transfer is given by

$$\phi_C=\rho c\,(a+bW)\,(T_S - T_A) \tag{15}$$

where T_S is the water surface temperature. The evaporation and conduction terms use the Bowen ratio assumption (Edinger et al. 1968, Henderson-Sellers 1984), wherein the same empirical expression for the transfer velocity ($a + bW$) is used to compute heat and mass (evaporation) transfer. The empirical coefficients a and b (Eqs. 14 and 15) have been found to exhibit variation in studies of evaporation and heat transfer at various sites (Chow et al. 1988). In order to estimate values for these coefficients for the Cannonsville site, prediction of ϕ_N from Eqs. 8 through 15 were compared to the estimates determined from the reservoir heat budget (Eq. 6 and Fig. 10b) for the 1995 monitoring period. The predictions were determined using daily averages of the on-site meteorological measurements and observed water surface temperatures. The estimated values (a = 0.4 m · sec^{-1} and b = 0.0025) were selected by minimizing the error between predictions and observations for the 1-week periods used in determining ϕ_N from the reservoir heat budget (Eq. 6), and resulted in a rms error of 29 watt · m^{-2} (Fig. 11b).

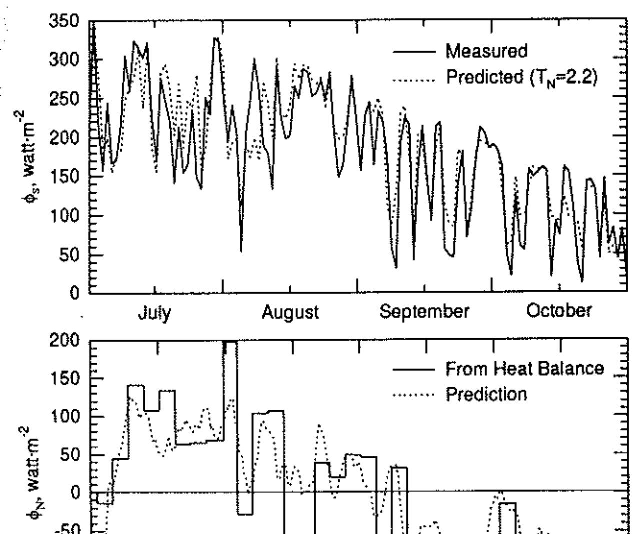

Figure 11.–Results of surface heat transfer analysis of Cannonsville Reservoir for 1995: (a) comparison of measured on-site solar radiation with predicted solar radiation using Eq. 9 with measurements of cloud cover at Binghamton and atmospheric turbidity T_N=2.2$; (b) net water surface heat flux determined from heat budget analysis, and predicted using optimized model coefficients a=0.4 m · sec^{-1} and b=0.0025.

Discussion

The observed interannual differences in thermal stratification characteristics in Cannonsville Reservoir are likely to be related to variations in reservoir operation (Fig. 4). A significant portion of the reservoir outflow during summer stratification has been dam release (Owens et al. 1986), which removes relatively cold water from the hypolimnion, reduces the volume of the hypolimnion and the stability of the water column, thus allowing fall turnover to occur more easily in response to surface cooling and wind mixing (Owens et al. 1986). Interannual differences in meteorological conditions also contribute to differences in stratification characteristics (Effler et al. 1986).

Simulation of the vertical variations in temperature associated with thermal stratification in Cannonsville Reservoir using a hydrothermal model requires that, at a minimum, a one-dimensional (vertical) model be used (Harleman 1982, Orlob 1983). The modest longitudinal variations in temperature may be described using a two-dimensional (laterally-averaged) model (e.g., Martin 1988). However, it is uncertain whether the additional model complexity associated with describing the longitudinal variations would make this worthwhile, considering the magnitude of longitudinal variations. Two mechanisms are likely to contribute to the longitudinal variations in temperature observed during the summer stratification period (Fig. 6). First, temperature differences between the tributaries and the reservoir surface waters were observed (Figs. 7 and 8). Moving from the river into the reservoir, it is expected that there would be a resulting gradient in temperature. The existence of such a temperature gradient could be used to identify the magnitude of longitudinal mixing in the reservoir, although a gradient in a conservative substance would be more useful (Owens 1998b). Second, assuming that the net surface heat flux ϕ_N is the same at all points, it would also be expected that the rate of heating or cooling in response to changes in meteorological conditions would be inversely proportional to the water depth. As a result, shallow upstream sites would be expected to warm more quickly in spring and cool more quickly in late summer and fall relative to deeper sites downstream.

The model for estimation of tributary temperature is a simple empirical approach, and is expected to be more accurate than the use of linear interpolation between infrequent, rapidly-varying measurements. Heat transport associated with inflow and outflow is a significant part of the heat budget of the reservoir (Fig. 10c), so that the accuracy of heat budget calculations in a hydrothermal model is dependent on the estimated inflow temperature. In addition, the relative temperature of a tributary and reservoir surface waters affects the flow pattern and extent of mixing at the mouth of the tributary. In particular, when a tributary is cooler and thus more dense than reservoir surface waters, a plunging inflow will tend to form, where the inflowing waters flow down the sloping reservoir bottom as a negatively buoyant current until its density is equal to that of the water column, where an interflow forms (Alavian et al. 1992). This process is potentially important for eutrophication modeling, in that nutrients contained in tributary inflow may not immediately enter the photic zone and be available to support phytoplankton growth.

In any type of predictive water quality modeling, it is desirable to determine the value of model coefficients from independent experiments or analyses that are conducted prior to application of the model rather than through model calibration (Chapra 1997). In this case, the value of the atmospheric turbidity T_N (Eq. 10) and the heat/mass transfer coefficients a and b (Eqs. 14 and 15) were determined without operating the hydrothermal model in which these coefficient values are used (Owens 1998a). As the back radiation, evaporative, and conductive flux components are each dependent on the water surface temperature, the nearly continuous measurements of the surface temperature (e.g., Fig. 6) reduce the uncertainty in the estimated coefficient values relative to that which would be obtained using weekly measurements. The value of the coefficients is in the range of that documented for other lakes and reservoirs (Harbeck 1958, Eagleson 1970, Chow et al. 1988).

The implications of this work for reservoir management are in the determination of characteristics of a predictive hydrothermal model to be used in the evaluation of management alternatives. The most important model characteristic is the dimensionality, as discussed above. The existence of tributary-reservoir temperature differences indicates that a hydrothermal model should have the capability of quantifying the resulting transport and mixing processes. The influence of inflow and outflow temperatures on the reservoir heat budget must be included in a hydrothermal model of the reservoir. The model for estimation of inflow temperature and the determination of surface heat transfer coefficients described here serve to increase the reliability (Chapra 1997) of hydrothermal model predictions.

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