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Calibration, Verification, and an Application of a Two-Dimensional Hydrothermal Model [CE-QUAL-W2(t)] for Cannonsville Reservoir[1]

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ABSTRACT

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The successful testing of a two-dimensional hydrothermal/hydrodynamic model, CE-QUAL-W2(t), for Cannonsville Reservoir is documented. The model is calibrated to the detailed temperature data collected in the reservoir (depth-profiles at six locations) over the April-November interval (weekly) of 1995, using comprehensive hydrologic and on-site meteorological forcing data. Further, the frequency of current oscillations predicted for the lower layers matched results of independent determinations made from thermistor chain deployments (two locations). The model is verified through the successful continuous simulation of the observed thermal stratification regime of the reservoir for the 1988-1994 interval, a period in which wide interannual differences were observed related to variations in meteorology and operations. The model performs well in simulating: 1) the timing of stratification and turnover, 2) the duration of stratification, 3) the dimensions of the epilimnion and hypolimnion, 4) the temperature of the layers, and 5) longitudinal variations in these features. The tested model is applied to characterize longitudinal transport of a conservative substance input at the mouth of the principal tributary as a pulse event (e.g., spill).

Key Words: two-dimensional, hydrothermal/hydrodynamic model, model testing, current oscillations, thermal stratification, temperature, conservative substance, tracer, CE-QUAL-W2.

Thermal stratification is common in deep lakes and reservoirs in temperate climates (e.g., Hutchinson 1957, Wetzel 1983) and is an important metabolic regulator of these systems. Features of stratification, such as its interplay with mixing, vertical dimensions of the layers, temperatures of the layers, and duration of stratification, mediate the cycling of materials, primary production, rates of biochemical reactions, and oxygen resources (e.g., Bowie et al. 1985, DiToro and Connolly 1980, Lam and Schertzer 1987, Martin et al. 1985, Owens and Effler 1989, Powell and Jassby 1974, Wodka et al. 1983). Dependence of various water quality measures on stratification has been noted by a number of investigators (e.g., Effler 1987, Orlob 1983, Owens and Effler 1989, Stefan et al. 1976, Stauffer and Lee 1973). Water motion and the features of stratification in lakes and reservoirs are dependent on several factors, such as basin morphometry (Ford and Stefan 1980)

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and setting, hydrology, and most importantly, meteorological conditions (Effler et al. 1986, Harleman 1982, Owens and Effler 1989). Substantial year-to-year variations in stratification are expected in temperate climates as a result of natural variations in meteorological conditions (Effler et al. 1986). Reservoirs can be subject to even greater year-to-year variability because of operational schemes (e.g., water supply and flow augmentation demands) that can result in highly dynamic hydrology and volume (e.g., Owens et al. 1998).

Models have been developed to simulate water motion and thermal stratification in lakes and reservoirs. Such fundamental physical information is of inherent interest to lake and reservoir managers. However, the greater utility of these quantitative tools has been as submodels that serve as the physical building blocks of water quality models (Harleman 1982, Martin 1988). Hydrothermal models predict the water motion and mixing that, together with source and sink (kinetics, loads and export) processes, determine the distribution of constituents in a water body.

This manuscript documents the calibration and verification of the hydrothermal component of CE-QUAL-W2 [Corps of Engineers, QUAL series model for 2-D water-bodies; Version 2.0; designated CE-QUAL-W2(t) hereafter], a two-dimensional model developed and maintained by the U.S. Army Corps of Engineers (Cole and Buchak 1995), for Cannonsville Reservoir, NY. Owens (1998a) has documented the calibration and verification of a one-dimensional hydrothermal model for the lacustrine zone (Effler and Bader 1998) of the reservoir. The two-dimensional model is successfully tested here for an 8-year period; a particularly rigorous test of the framework because of its duration and the wide range of conditions observed in the interval (Effler and Bader 1998, Owens 1998b). Additional contributions of this work include: 1) presentation and demonstration of a protocol to improve hydrothermal model performance when off-site wind data must be used; 2) validation of temporal features of the model's performance in simulating transport and mixing in the reservoir's hypolimnion; and 3) application of the tested model to determine time-of-travel and dilution of hypothetical pulse inputs from the mouth of the primary inflow to the water supply intake(s), for a range of meteorological and runoff conditions.

Cannonsville Reservoir

Cannonsville Reservoir is a Y-shaped impoundment (Fig. 1) located in Delaware County, NY, approximately 190 km northwest of New York City (NYC). The reservoir

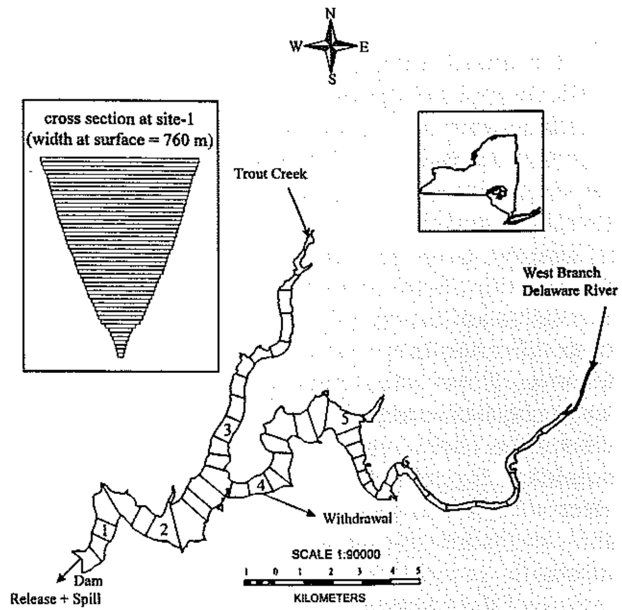

Figure 1.–Cannonsville Reservoir; inflow and outflow locations, monitoring sites, and computational grid for CE-QUAL-W2(t) model.

is owned by NYC and operated by the New York City Department of Environmental Protection (NYCDEP) as a supply for drinking water for NYC and to augment flow in the Delaware River downstream of the reservoir. Cannonsville Reservoir has a capacity of 3.63×10^8 m^3, a mean depth (when full) of ~ 19 m, and an average flushing rate of 2.6 times·y^1 (Owens et al. 1998).

Water leaves the reservoir by one of three pathways: flow over the spillway, which occurs when the water surface elevation (WSE) is above the crest elevation (350.6 m, MSL); drinking water withdrawals; and releases at the base of the dam to downstream portions of the Delaware River. Drinking water withdrawal occurs at a mid-reservoir intake structure (Fig. 1); water can be withdrawn at depths of 10, 20 or 37 m below the spillway crest (the middle intake is most often used). The release works at the dam consist of several 2.2-m-diameter pipes, at a depth of about 45 m below the spillway crest. NYCDEP continuously monitors all three outflow pathways and WSE. NYC may meet the downstream flow requirements with releases from Cannonsville, Pepacton, or Neversink Reservoirs.

The largest portion of the inflow reaching Cannonsville Reservoir is from the West Branch of the Delaware River (WBDR; Fig. 1), which drains about 80% the impoundment's watershed. Substantial year-to-year and seasonal differences in the various components of the reservoir's hydrologic budget (e.g., WSE) occur, associated with variations in runoff and operation strategy (Owens et al. 1998). Owens et al. (1998) have reviewed the components of the reservoir's hydrologic budget for the period of operation and developed a hydrologic model that maintains the requisite flow balance required for CE-QUAL-W2(t).

Cannonsville Reservoir is dimictic (Effler and Bader 1998, Owens 1998b); it experiences stratification during summer, turnover in fall and spring, and winter ice-cover (inverse thermal stratification under the ice). The depth of the epilimnion is rather shallow (e.g., ~ 6 m); thus, a relatively large portion of the reservoir's volume is isolated from the atmosphere during summer stratification. Significant longitudinal differences in thermal stratification only emerge soon after the onset of stratification in spring and close to the onset of fall turnover. Noteworthy lateral structure in stratification has not been observed (Effler and Bader 1998). Detailed thermistor chain measurements in 1995 identified dominant frequencies of current oscillation in the reservoir's lower waters (Owens 1998c). Empirical analysis (Effler and Bader 1998) indicates that the substantial year-to-year differences in the stratification regime of the reservoir are influenced importantly by interannual differences in reservoir operation. For example, the duration of stratification was found to be shorter in years of greater drawdown (low summer average WSE; Effler and Bader 1998).

Cannonsville Reservoir is eutrophic (e.g., Effler and Bader 1998), manifested as high standing crops of phytoplankton, blooms of nuisance blue-green algae, low clarity, and severe depletion of oxygen in the hypolimnion. Substantial gradients in some of these trophic state indicators prevail between the riverine, transition, and lacustrine zones of the reservoir (Effler and Bader 1998). Noteworthy differences in water quality characteristics have not been observed along lateral transects (Effler and Bader 1998). A two-dimensional transport/hydrodynamic (sub)model will be necessary to support simulation of the prevailing longitudinal gradients in water quality. Available water quality data for the reservoir do not support the need for a three-dimensional transport framework for this system (e.g., Effler and Bader 1998).

Modeling

Model Description

CE-QUAL-W2(t) uses laterally averaged two-dimensional (vertical and longitudinal) equations of fluid motion (Edinger and Buchak 1975). Inherent to this framework is the assumption of uniform lateral mixing in the cross channel direction. The basic equations that describe horizontal momentum, free water surface elevation, hydrostatic pressure, continuity, equation of state, and constituent transport (temperature in this application) were presented by Edinger and Buchak (1975). Six equations result in six unknowns: water surface elevation, pressure, horizontal velocity, vertical velocity, density, and temperature. The exact forms of these equations, the numerical solution techniques and other auxiliary functions of the model, are described by Cole and Buchak (1995).

The heat budget of the model includes terms for evaporative heat loss, short- and long-wave radiation, convection, conduction, and back radiation (Cole and Buchak 1995). The model requires air temperature, dew point temperature, wind, and cloud cover (or direct measurements of solar radiation). Inflow, inflow temperature, and outflow from the lake/reservoir must also be specified. CE-QUAL-W2(t) represents a water body in the form of a grid of cells consisting of longitudinal segments (see Fig. 1) and vertical layers. The geometry of the computational grid is determined by longitudinal spacing of segments (i.e., lengths), vertical spacing of layers (i.e., heights), and average cross sectional widths. Certain features of the structures regulating outflows [e.g., spillway length, depth of water supply withdrawal(s), depth of dam outlet(s)] must also be specified.

CE-QUAL-W2(t) has several coefficients that may be adjusted in the calibration process (Table 1). The

Table 1.–Coefficients in CE-QUAL-W2(t) for Cannonsville Reservoir application.

Coefficient	Symbol	Cannonsville Reservoir Value
Longitudinal eddy viscosity	A_x	$1\ m^2 \cdot s^{-1}$
Longitudinal eddy diffusivity	D_x	$1\ m^2 \cdot s^{-1}$
Chezy coefficient	C_h	$70\ m^{0.5} \cdot s^{-1}$
Wind sheltering coefficient	W_{sc}	0.85
Fraction of incident solar radiation absorbed at the water surface	b	0.45
Coefficient of bottom heat exchange	C_{BHE}	$7 x 10^{-8}\ W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

values of the coefficients for longitudinal eddy viscosity and diffusivity, Chezy coefficient, and wind sheltering directly affect hydrodynamics which in turn affect in-reservoir temperatures. The other two coefficients, the fraction of incident solar radiation absorbed at the water surface and the coefficient for bottom heat exchange, directly affect the heat budget.

Development of Model Inputs

Cannonsville Reservoir was represented by 56 longitudinal segments (Fig. 1) and 50 vertical layers, consistent with guidelines for defining the computational grid presented by Cole and Buchak (1995). Segment boundaries were first established on a contour map for the basin. Dimensions of the segments (including individual layers) were then obtained from analysis of a digitized contour map of the reservoir with ArcInfo® software. The lengths of the segments range from 417 to 1160 m, and widths range from 25 to 1356 m. The layer thickness is 1 m.

Hydrologic inputs (inflows, outflows, WSE) to CE-QUAL-W2(t) were those incorporated in the hydrologic model for the reservoir (Owens et al. 1998). The WBDR (≈80% of the total) and Trout Creek (≈5% of the total) inflows were input to their respective segments (Fig. 1). The remaining small ungauged (or direct) inflows (≈15% of the total) were distributed along the segments of the Trout Creek arm of the reservoir. Outflows from the reservoir via spillway, dam-release, and withdrawal-works represented 40%, 32%, and 28%, respectively, of the total outflow from the reservoir (Owens et al. 1998). All inflows and outflows were specified as daily average values. These flow time series represent the inflow and outflow boundary conditions for the model.

Temperature has been monitored bi-weekly near the mouths of WBDR, Trout Creek, and Loomis Creek (a minor tributary) since 1988. Daily inflow temperatures were determined by a simple empirical model, based on air temperature (Effler and Owens 1986, Owens 1998b). These tributary temperatures constitute the inflow temperature boundary conditions for the model. The most temporally detailed monitoring database for reservoir temperature (profiles) was that collected in 1995 (weekly April-November). Less frequent (bi-weekly to monthly) data are available for the 1988-1994 interval. Approximately the same six monitoring sites (Fig. 1) were used in the 1995 study and the earlier program, extending from near the mouth of WBDR to the dam, and including a station in the Trout Creek arm (Effler and Bader 1998). The in-reservoir temperature profiles represent the primary basis to evaluate the performance of this hydrothermal model. A thermistor chain was deployed at site 1 for about 6 weeks in 1995 to measure temperature fluctuations at fixed depths over time. Details of those measurements and related data analyses are presented by Owens (1998c). Additionally, irradiance profiles were collected at all six sites routinely in 1995, and the values for the attenuation coefficient for downwelling irradiance (k_d, m^{-1}) were calculated (Effler et al. 1998).

To support model testing, a meteorological station was installed at the dam in November of 1994. This station provided on-site hourly measurements of air temperature, relative humidity, wind speed and direction, and total incident solar radiation. Dew point temperature was computed from relative humidity and air temperature according to Linsley et al. (1982). These meteorological data constitute the surface boundary conditions required by the model. Model simulations for the period prior to 1995 were supported by off-site meteorological data collected at a NWS station at Binghamton, NY, located ~ 64 km northwest of the reservoir. Model sensitivity analyses of meteorological inputs indicated the principal uncertainty in thermal stratification simulations is associated with wind speed, and that systematic deterioration in model performance occurs when the off-site (instead of on-site) data are used to drive the model. The paired on-site and off-site wind data available for 1995 were analyzed to develop relationships to adjust the off-site wind data to better represent conditions at the reservoir. No significant correlation was observed between paired hourly wind speeds (scalar) for the two sites for the complete 1995 interval, however, daily average wind speeds were well correlated ($R = 0.77$; Fig. 2a). There was substantial seasonality in the relationship; a monthly time segmentation was adopted for this analysis. The value of R varied from 0.62 to 0.89 for the 12 months of 1995 (e.g., the relationship for May 1995 is shown in Fig. 2b). These findings indicate daily average wind speed at the reservoir can be reasonably estimated, with some adjustment (e.g., Fig. 2b), from daily average wind speed measurements made at Binghamton.

Wind inputs at a hourly time step are recommended to support accurate simulations with CE-QUAL-W2(t) (Cole and Buchak 1995). Three distributions were developed from on-site 1995 data to specify variations (1-hour time step) of wind speed within a day, for each month (i.e., total of 36 distributions). The distributions correspond to minimum, median, and maximum daily average wind for each month (Fig. 2c). One of the three distributions was selected, for any given day, for which the observed daily average wind speed was closest to the estimated daily average wind speed, and applied to the estimated daily average wind speed to yield the adjusted hourly wind speed input. The protocol for

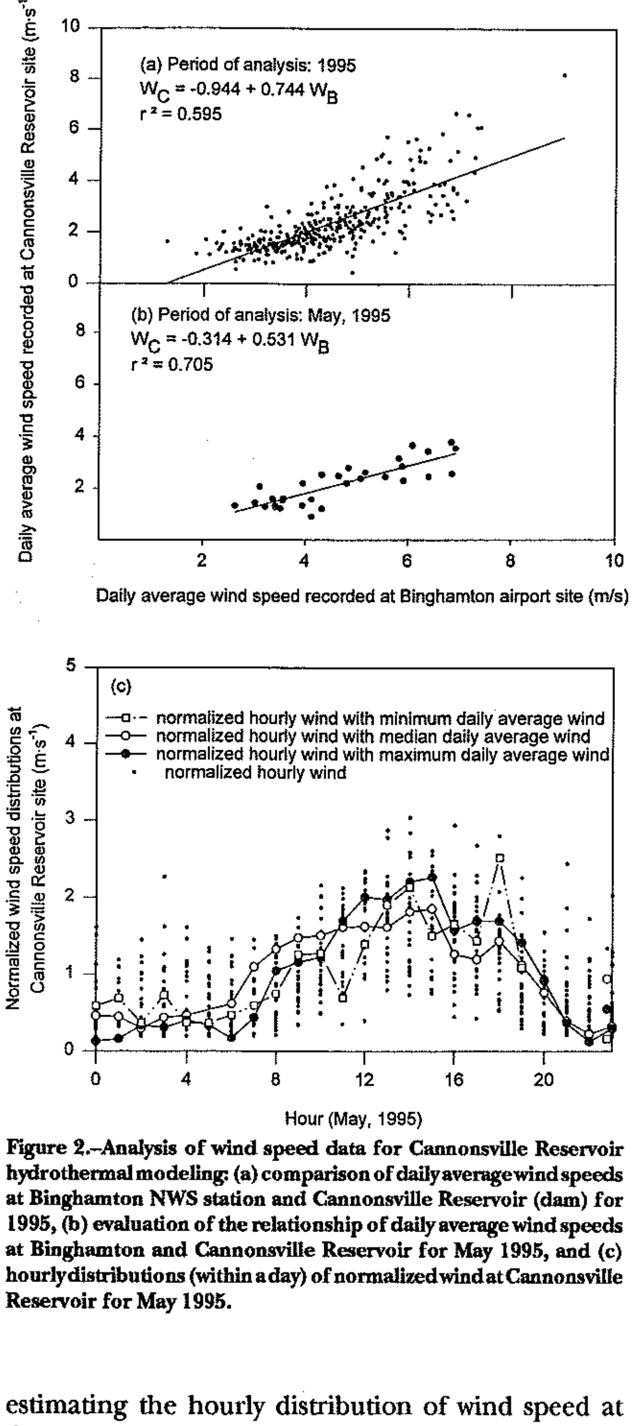

Figure 2.–Analysis of wind speed data for Cannonsville Reservoir hydrothermal modeling: (a) comparison of daily average wind speeds at Binghamton NWS station and Cannonsville Reservoir (dam) for 1995, (b) evaluation of the relationship of daily average wind speeds at Binghamton and Cannonsville Reservoir for May 1995, and (c) hourly distributions (within a day) of normalized wind at Cannonsville Reservoir for May 1995.

estimating the hourly distribution of wind speed at Cannonsville Reservoir from measurements at Binghamton is specified by the relationship

$$U_{C,h} = \{s_m x \overline{U}_B + b_m\} \, x \, \frac{U_{C,h,m,d,95}}{\overline{U}_{C,m,d,95}} \qquad (1)$$

where, h = 1,2,3, ... 24 hours; m = 1,2,3, ... 12 months; d = distribution type; b_m and s_m are the intercept and slope of linear regression (e.g., Fig. 2b); $U_{C,h}$ = hourly wind speed at the Cannonsville Reservoir site; $\overline{U}_B$ = daily average wind speed at Binghamton airport; $U_{C,h,m,d,95}$ and $\overline{U}_{C,m,d,95}$ = hourly and daily average wind speed at the Cannonsville Reservoir site for 1995 in month "m" for distribution "d" (e.g., Fig. 2c). Wind directions were kept the same as observed at Binghamton because temperature predictions were found to be rather insensitive to direction. A comparison of air and dew point temperatures measured at Cannonsville Reservoir and Binghamton for 1995 established that these parameters are essentially equal at the two sites. Therefore, for model simulations of the pre-1995 period, air and dew point temperatures recorded at Binghamton airport were used. Incident solar radiation for the pre-1995 period was estimated from cloud cover internally by the model (Cole and Buchak 1995).

Setup and Testing

The model's autostepping algorithm (Cole and Buchak 1995) calculates a maximum time-step, within a specified range, based on hydrodynamic numerical stability requirements and then uses a fraction of this value for the actual time-step. The minimum and maximum time-steps used were 1 s and 1 h, respectively. The framework of CE-QUAL-W2(t) was modified to accept independent specification of light extinction coefficient (k_d), instead of the internal calculation from the water quality portion of CE-QUAL-W2 (Cole and Buchak 1995). The value of k_d varies in time and space in the reservoir (Effler et al. 1998). However, model simulations were insensitive to these variations [e.g., most k_d values were within the range 0.3 to 0.9 m^{-1} in 1995 (Effler et al. 1998)]. Thus, a temporally and spatially averaged value of 0.55 m^{-1} was adopted for all simulations.

The model was calibrated for the April-November period of 1995. This interval was selected because of the availability of: 1) the most temporally and vertically detailed temperature data for the reservoir, 2) on-site meteorological data, and 3) current and thermistor chain measurements (Owens 1998c). The values of the model coefficients adopted (Table 1) correspond to the "default" values (Cole and Buchak 1995). These "default" values are appropriate for a number of systems (Bath and Timm 1994, Dortch and Boyt 1983, Martin 1988), and are recommended by Cole and Buchak (1995). The calibrated model was then verified (i.e., no change in coefficients from calibration values) for the 1988-1994 interval, as a single continuous simulation. This represents an especially rigorous testing of the model, as it includes rather wide ranges of forcing conditions. A particularly wide range of hydrologic conditions and WSEs are included in this interval (see Owens et al. 1998).

Evaluation of Model Performance

Model performance was evaluated both qualitatively and quantitatively. Salient features of the stratification regime on which model simulations were evaluated include: 1) the timing of the onset of stratification in spring and turnover in fall, 2) the duration of stratification, 3) the dimensions of the stratified layers (e.g., epilimnion and hypolimnion), 4) the temperatures of the stratified layers, 5) the overall temperature differences in the water column, and 6) the frequency of current oscillations in the lower stratified layers. These features of the hydrodynamics and hydrothermal regimes are described for the reservoir by Owens (1998b).

The quantitative basis of evaluating model performance adopted was the "root mean square error" (RMSE) statistic (e.g., Thomann 1982), calculated according to:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(X_{i,obs} - X_{i,prd})^2}{N}} \qquad (2)$$

where, N = number of observations, $X_{i,obs}$ = observed value of *i*th observation of parameter X, and $X_{i,prd}$ = predicted value of *i*th observation of parameter X. RMSE is statistically well behaved and is an indicator of the average error between observations and predictions. Generally, a lower RMSE implies a better model fit to observations.

Model Performance

The performance of CE-QUAL-W2(t) is evaluated in four different formats: 1) as individual thermal profiles in time and space, 2) as time plots of selected features of the thermal stratification regime that depict seasonality, 3) as the major frequencies/periods of oscillations of bottom currents, and 4) as summary statistics that represent a feature of the stratification regime for a major part of the year.

Mid-month predictions of thermal stratification in 1995 matched well the measured profiles from site 4 (Fig. 3). The RMSE (calculated from observations at all sites for all days of sampling) value for 1995 was 1.17 °C. The simulations track the progression from essentially spring turnover (e.g., Fig. 3a) to peak summer stratification (e.g., Fig. 3d and e), the subsequent deepening of the epilimnion (e.g., Fig. 3f) and onset of nearly complete fall turnover (e.g., Fig. 3g). Timing, temperatures, and dimensions of the layers are simulated well. Note the progressive lowering of WSE

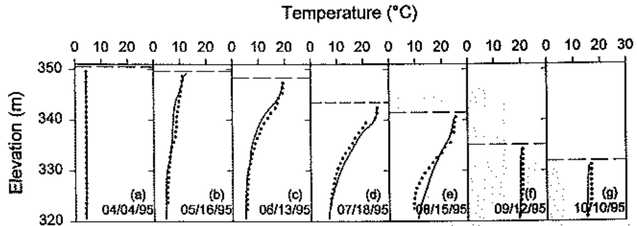

Figure 3.–Calibration of CE-QUAL-W2(t) to observations in Cannonsville Reservoir for 1995 at site 4, as temperature profiles: (a) April 18, (b) May 16, (c) June 13, (d) July 18, (e) August 15, (f) September 12, and (g) October 10.

that occurred during the calibration period (Fig. 3). The relatively thin stratified layer that persisted at the reservoir bottom in early fall has been attributed to an underflow, made more dense by the lower (relative to the reservoir) temperature of the WBDR during this interval (Owens 1998c). Though underflows/interflows are accommodated by the framework, they were not a focus of this model testing effort, because the phenomenon did not play a prominent role in the reservoir's stratification regime.

Alternatively, model performance in 1995 is evaluated through comparison of time series of observations and simulations of epilimnetic and hypolimnetic volume-weighted temperatures. Model performance in this format is presented here for sites 1 and 6 (Fig. 4a and b, respectively), which clearly depicts the timing of stratification, the heating and subsequent cooling of the epilimnion, and the progressive heating of the hypolimnion. Again the high performance of the model is demonstrated. Further, the utility of the two-dimensional capability is shown, as certain disparate features of the stratification regimes of these two sites are faithfully captured, for example, the more rapid heating in spring and shorter duration of stratification at site 6 (Fig. 4b) compared to site 1 (Fig. 4a).

A more detailed representation of the two-dimensional (longitudinal) performance of the model is presented for a single day in 1995 (May 9) by comparison of the simulated and observed profiles for each site (Fig. 5a-f). This date was chosen because longitudinal gradients in thermal characteristics were most pronounced in spring (and fall), when temperature differences between the air and the reservoir, and WBDR and the reservoir, were greatest. The extent of longitudinal differences on this date is dramatized by the comparison of the simulations for the various sites on a single plot (Fig. 5g). The model performed well in simulating the longitudinal structure in thermal stratification in the reservoir on May 9, 1995 (Fig. 5), as well as on other days of the calibration period (e.g., Fig. 4a and b).

Transport and mixing in the hypolimnion of lakes and reservoirs are strongly influenced by motion

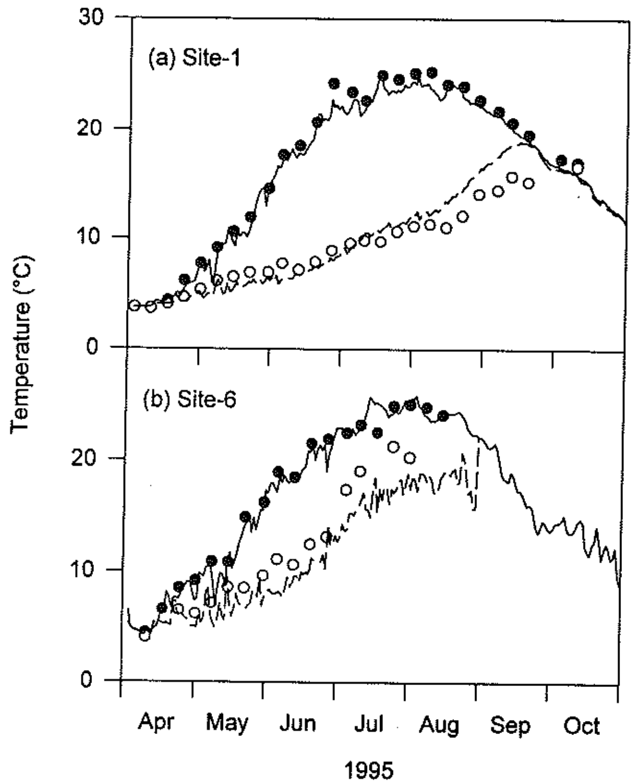

Figure 4.–Calibration of CE-QUAL-W2(t) to observations in Cannonsville Reservoir for 1995, as time series of epilimnetic and hypolimnetic temperatures: (a) site 1, and (b) site 6.

associated with internal waves or seiches (Fischer et al. 1979). Spectral analysis (see Lemmin and Mortimer 1986) of a time series of temperature measurements made in the reservoir hypolimnion at site 1 depicted the presence of characteristic periods of oscillation associated with internal waves (Fig. 6; see Owens 1998c). These periods were 43 h and in the range of 14 to 17 h (Fig. 6). CE-QUAL-W2(t) was used to predict variations in hypolimnetic temperatures at this same location for the period of deployment of the thermistor chain. An analysis of the predicted time series of temperature yields a spectra (Fig. 6) with very similar characteristic periods. This analysis indicates that CE-QUAL-W2(t) captured the characteristics of water motion which

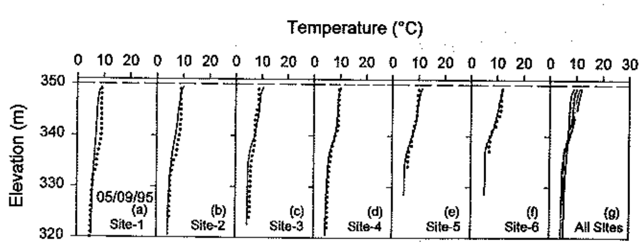

Figure 5.–Calibration of CE-QUAL-W2(t) to observations in Cannonsville Reservoir for 1995, as temperature profiles for six longitudinal sites: (a) site 1, (b) site 2, (c) site 3, (d) site 4, (e) site 5, (f) site 6, and (g) simulations for all sites.

influence transport and mixing in the hypolimnion of the reservoir.

Model verification is demonstrated by comparisons of simulations to selected monthly profiles at site 4 in 1994 [Fig. 7(a-g)]. Further, the benefit of adjusting the off-site wind measurements made at Binghamton, described previously (e.g., see Fig. 2), is demonstrated (Fig. 7). As observed for the calibration year (Fig. 3), the simulations of 1994 track well the vertical and seasonal character of the thermal stratification regime of the reservoir (Fig. 7). Systematic improvements in model performance were achieved by the wind adjustment protocol (e.g., Fig. 7); specifically, the "global" RMSE value of the verification simulations (i.e., off-site wind data with adjustment) was 1.70 °C, compared to the higher value of 2.26 °C obtained with the use of the unadjusted off-site Binghamton wind data.

Verification over the entire 1988-1994 interval is demonstrated for site 1 of the reservoir by the comparison of the time series of the continuous simulation of epilimnetic and hypolimnion temperatures to the

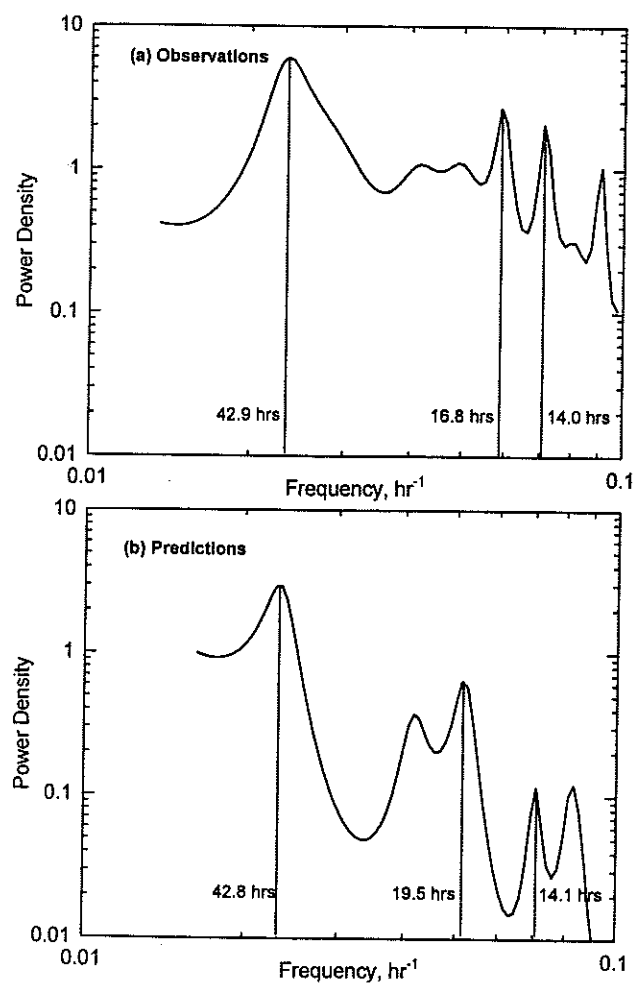

Figure 6.–Spectra of time series of temperature in the hypolimnion of Cannonsville Reservoir in 1995: measured (Owens 1998a) and predicted by CE-QUAL-W2(t).

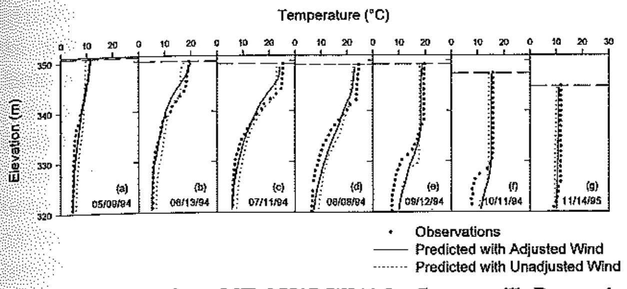

Figure 7.–Verification of CE-QUAL-W2(t) for Cannonsville Reservoir for 1994 at site 4, as temperatures profiles: (a) May 9, (b) June 13, (c) July 11, (d) August 8, (e) September 12, (f) October 11, and (g) November 14. Comparison of model performance using adjusted and unadjusted wind speed data collected at Binghamton.

observations (Fig. 8). The various features of the regime – timing of turnover, duration of stratification, and temperatures of the layers – were well simulated in all years (Fig. 8; range of RMSE = 1.37 °C to 1.70 °C). The heat budgets of the epilimnion tended to be more accurately simulated than for the hypolimnion. Note that the temperature of the hypolimnion remained colder in 1994, a year in which there was relatively modest drawdown, compared to 1995, in which a major drawdown was experienced (Owens et al. 1998). The next longest successful simulation with a hydrothermal model we are aware of is that presented by Owens and Effler (1996) for Onondaga Lake, NY (6 years).

The model performed well ($r^2 = 0.64$) in simulating the observed year-to-year differences in the duration of summer stratification (e.g., site 1; Fig. 9). Some of the uncertainty in this feature of the model's performance is attributable to monitoring frequency (Fig. 9). This feature of the stratification regime has important water quality implications, particularly with respect to the oxygen resources of hypolimnia (Lam and Schertzer 1987, Martin et al. 1985). The duration of stratification is influenced by meteorological conditions (e.g., Effler et al. 1986), but more important for this reservoir is the extent of drawdown. For example, the duration of stratification is shorter in years in which greater drawdown is experienced (Effler and Bader 1998).

A Model Application

System response to contaminant spills in watersheds is a ubiquitous concern to managers of water supply reservoirs and lakes. Important features of the response include: 1) the time of travel from the watershed to water supply intakes, 2) peak contaminant concentrations (e.g., maximum risk) at the intakes, 3) the time course of contaminant concentrations at the intakes (e.g., duration of risk), and 4) the vertical distribution of the contaminant. Reliable simulations of system responses may serve to guide effective management action, such as the timing for use of alternate supplies or modifications in operations to selectively discharge or avoid (e.g., depth of water supply withdrawal) the contamination. Here we demonstrate the application of the two-dimensional hydrothermal/hydrodynamic model to preliminarily address the response characteristics of Cannonsville Reservoir to event loads (e.g., spills) of an undefined contaminant. This application emphasizes the longitudinal capabilities of the model, similar to river "spill" models (see Chapra 1997), though vertical distribution is also simulated.

Several factors will influence the response of a reservoir to a contaminant spill, including: 1) the character of the spill (timing, quantity), 2) the reactivity (e.g., kinetics) of the contaminant, 3) the density of the inflow carrying the spill (e.g., overflow, underflow, interflow), 4) the magnitudes of the inflow and reservoir volume, 5) prevailing features of density stratification in the reservoir, 6) reservoir operation during the spill, and 7) prevailing meteorology. No effort is made here to exhaustively analyze all these interactions. Instead we analyze two scenarios that may bracket many of the

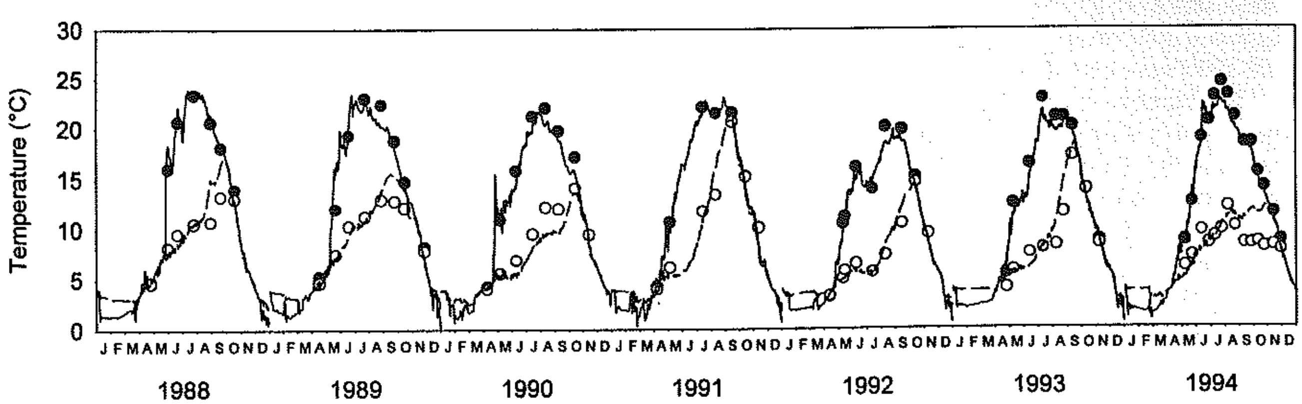

Figure 8.–Comparison of observed and predicted epilimnetic and hypolimnetic temperatures at site 1 of Cannonsville Reservoir for the period 1988-1994.

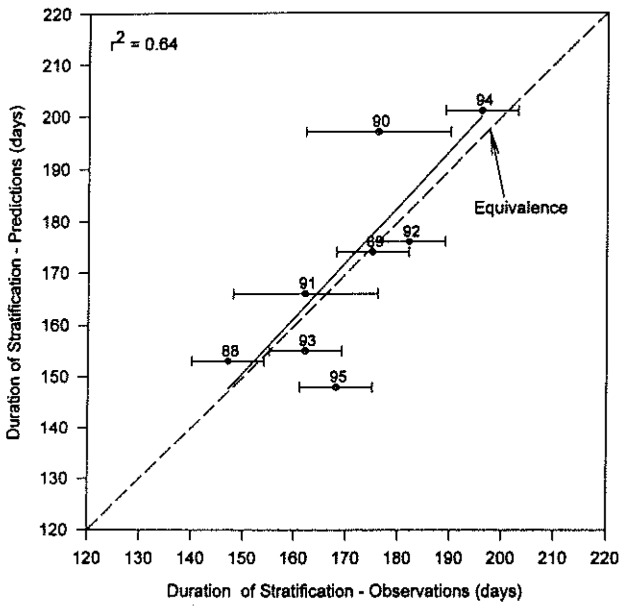

Figure 9.–Comparison of observed and predicted duration of stratification in Cannonsville Reservoir, at site 1, for 1988-1995. Individual years identified by the last two digits; equivalence line included. Error bars represent uncertainty in observations associated with monitoring frequency.

possibilities for this system, one corresponding to a rather full reservoir case (1994) and the other a major drawdown case (1995), to demonstrate this form of application of the tested model and depict the general character of response to be expected for this reservoir.

One hundred metric tonnes of conservative contaminant "X" was spilled into the mouth of WBDR, at Beerston (Fig. 1) for a 2-day period (e.g., square wave input load; Thomann and Mueller 1987), over the period May 20-22 (e.g., beginning of stratification period). The WBDR tends to be warmer than the surface waters of the reservoir during that interval and thus becomes initially incorporated into the epilimnion. Concentrations of contaminant "X" just downstream of the spill were established by the WBDR flow; the concentrations in the WBDR mouth for the 1994 and 1995 cases were 34 and 80 mg·L^{-1}, respectively. Hydrologic and meteorological conditions measured in 1994 and 1995 were specified.

Simulations for the two cases are presented for the three water supply intakes for the May-November interval (Fig. 10a and b). Several noteworthy differences in the reservoir's response to a spill are predicted for the full versus drawdown cases. In less than 1 week following the spill, concentrations of contaminant "X" are predicted to increase at the upper (10 m below spillway) intake for the 1994 case, whereas the response time is more than 2 weeks for the lower inflow/greater drawdown case of 1995. Peak concentrations are predicted at the upper intake by about mid-July for both cases. The lower (~ 0.5X) peak value for the nearly full reservoir case of 1994 reflects the influence of greater dilution associated with the greater inflows and reservoir volume. Increases at the deeper intakes are delayed for both cases because of the limited isolation offered by the attendant density stratification. Progressive increases are predicted at the two deeper intakes, with the response being the most delayed at the deepest intake (37 in below spillway). These increases are mediated by vertical mixing-based inputs from the overlying contaminated epilimnion. Contaminant "X" concentrations are predicted to converge for the upper and middle intakes by late August, under 1994 conditions (Fig. 10a; drawdown of only ~ 2m), associated with the deepening of the upper mixed layer at that time. The subsequent temporary inversion (Fig. 10a; middle intake concentrations > upper intake concentration) was driven by a major runoff event that had a diluting effect at the depth of the upper intake. The predicted concentration decreases at the upper intake for 1995 conditions from mid-August to early September (Fig. 10b), associated with dilution from mixing with underlying layers. The termination of the simulation for the upper intake in early September (Fig. 10b) corresponds to the WSE dropping below this

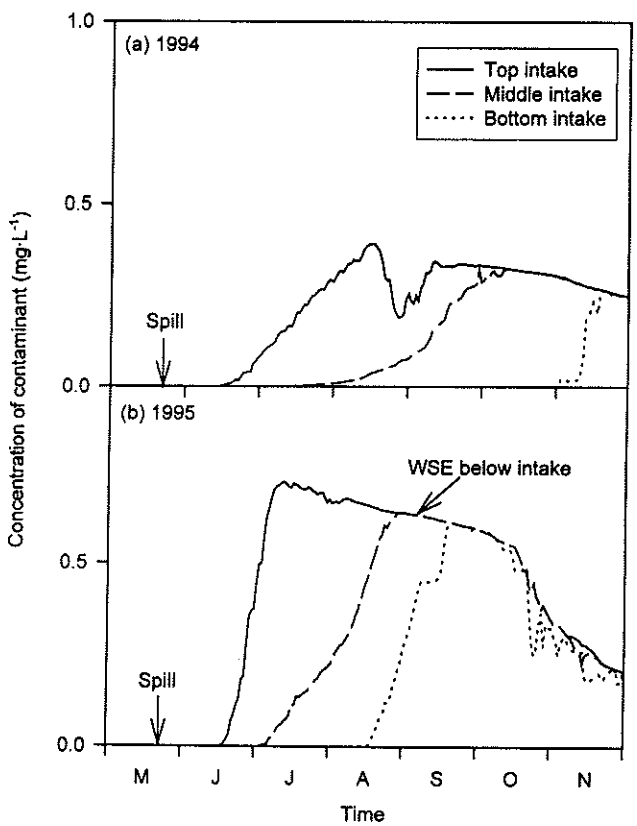

Figure 10.–Time response of Cannonsville Reservoir at the water supply intakes to a 100-metric-ton spill of conservative contaminant "X" for two (combined) hydrology/meteorology cases: a) 1994, and b) 1995.

elevation. The differences in the timing of convergence of concentrations at the bottom intake with values at overlying intakes are largely driven by inter-annual differences in the extent of drawdown of the reservoir. Convergence was predicted for early November for the 1994 case (Fig. 10a) versus mid-September for the 1995 case (Fig. 10b). The stronger decreases predicted in October and November in 1995 reflect the much higher inflows (i.e., dilution) in that interval compared to 1994.

Certain features of this spill analysis may have value for reservoir managers. Contaminants spilled near the mouth of WBDR could reach the upper intake in several days (e.g., high runoff/full reservoir conditions). NYCDEP's existing practice of taking water primarily from the middle intake offers an extra level of protection with respect to response time to spills. Yet greater avoidance of contaminant spills would be offered by the deepest intake, under the conditions addressed in this analysis. The analysis of a wider range of spill scenarios would doubtless yield additional insights for managers of this system.

Summary

The credibility of the hydrothermal/hydrodynamic portion of the two-dimensional simulation model CE-QUAL-W2(t) has been rigorously tested for application to Cannonsville Reservoir. The model was calibrated to the comprehensive temperature data set collected at the reservoir over the April-November interval of 1995, using detailed hydrologic and on-site meteorological forcing data. Further, the frequency of current oscillations predicted for the lower layers matched independent determinations made in 1995. The model was verified through the successful continuous simulation of the varied thermal stratification regime observed for the reservoir over the 1988-1994 interval, using off-site meteorological data. The model accurately simulates all the important features of the stratification regime of the reservoir. Thus the model may be used to evaluate related management issues for the reservoir, including the effects of reservoir operation, manifested in the stratification and mixing regimes of the reservoir and the temperatures of its outflows. Further, the model represents an appropriate transport framework to support a water quality model intended to simulate conditions temporally in both the vertical and longi-tudinal dimensions [i.e., two-dimensional water quality model(s)]. The potential management utility of the model is demonstrated through a preliminary appli-cation that depicts the response of the reservoir at the water supply intakes to a hypothetical spill of a conservative contaminant at the mouth of WBDR, for 2 years of disparate hydrology and operation.

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