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A Strategy for Reservoir Model Forecasting Based on Historic Meteorological Conditions[1]

E. M. Owens
Department of Civil and Environmental Engineering
Syracuse University
Syracuse, NY 13244

S. W. Effler, S. M. Doerr and R. K. Gelda
Upstate Freshwater Institute
P.O. Box 506
Syracuse, NY 13214

E. M. Schneiderman, D. G. Lounsbury and C. L. Stepczuk
New York City Department of Environmental Protection
Valhalla, NY 10595

ABSTRACT

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A strategy for the application of linked watershed and reservoir models in the analysis of water quality management proposals for a water supply reservoir is presented. This strategy is based on the use of a long-term historical record of meteorological data, so that the predicted changes in water quality may be evaluated by considering the variations in streamflow, material loading, reservoir heat transfer and mixing associated with natural variations in meteorological conditions. Model simulations for a baseline condition and for several management proposals involving point source nutrient control, nonpoint source nutrient reduction, and reservoir operations are presented. The predictions are presented as distributions of the frequency of occurrence of selected annual statistics of nutrient loading, reservoir stratification, and reservoir water quality. Simulations for Cannonsville Reservoir indicate that reductions in phosphorus loading from wastewater treatment plants in the watershed would have a greater impact on summer average chlorophyll concentrations than nonpoint phosphorus control, and that reservoir operations that result in a decrease in reservoir drawdown result in improved reservoir water quality.

Key Words: water quality models, water quality management.

Models are often used in the analysis of reservoir operation and management programs (Loucks et al. 1981). Where management of water quantity only is of concern, models may be sufficiently simple so that mathematical programming techniques, such as linear programming, may be used to determine a reservoir operation policy or rule which optimizes an objective function which quantifies net economic benefits, hydroelectric energy production, or other measures of system performance (Yeh 1985). In such models, reservoir characteristics and the water balance (continuity) statement are expressed as constraints. Models that directly determine optimum policies for reservoirs using mathematical programming where the objective function considers water quality have not been developed (Dandy and Crawley 1992). Rather, water quality models are of the simulation type (Yeh 1985, Wurbs 1993), where water quality is predicted based on a specified time series of environmental and operation conditions. Repetitive or iterative simulations may be made in order to analyze the performance of proposals for water quality management (Wurbs 1993).

When applying models based on either

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mathematical programming or simulation, the time series of environmental conditions under which the model is operated must be specified. For the case of water quantity studies, a time series of streamflow from the reservoir watershed must be specified using historical streamflow measurements that have been adjusted to be representative of the location of interest and specified state of watershed development (Wurbs 1993). This time series may be either: (1) adjusted streamflow measurements for the period of record; (2) adjusted streamflow measurements for a selected "critical" portion of the period of record; or (3) synthetic streamflows. A synthetic time series, which exhibits selected statistics, is used when the period of record of historical measurements is of short duration or is otherwise judged to not be representative of the entire range of conditions that may be encountered in the future (Yeh 1985).

In addition to streamflows, reservoir water quality models require that time series of material loading associated with streamflow, and of certain meteorological quantities, be specified (Orlob 1983). In that land use, agricultural, and waste management practices in the watershed are often considered together with operations in managing reservoir water quality, a watershed model may be used to simulate the affect of management practices in the watershed on streamflow and material loading (Haith and Shoemaker 1987). A watershed model that is capable of simulating a time series of streamflow and material loading itself requires an input time series of precipitation and, in colder climates, other meteorological conditions which affect snowmelt.

We consider here the application of linked watershed-reservoir simulation models, where management activities in the watershed and of the reservoir outlet works are evaluated for a specified time series of meteorological conditions (Fig. 1). The meteorological quantities included in the time series are precipitation and quantities necessary to predict snowmelt (e.g., air temperature). Depending on the particular nature of the reservoir model, the meteorological quantities would also include those necessary to simulate water surface heat and gas transfer, internal mixing, and light intensity in the water column. These quantities are likely to include wind speed and direction, air temperature and moisture, and incident solar radiation. As in the case of streamflow time series as described above, a meteorological time series may be historical measurements for the entire period of record, a critical subset of the entire record, or a synthetic time series. However, while techniques for generating a synthetic univariate meteorological time series have been developed (Carey and Haan 1978), procedures which generate a multivariate series have not.

A reservoir water quality model that is capable of simulating the seasonal dynamics of phytoplankton biomass in Cannonsville Reservoir has been presented previously (Doerr et al. 1998). In addition, a model that simulates streamflow and material loading for the watershed of this reservoir has also been developed and tested (Schneiderman et al. 1998). Here we describe the linkage of these models to allow evaluation of water quality management practices related to point and nonpoint sources of streamflow and nutrients in the watershed, and reservoir operations. A strategy for application of these models for this purpose that is based on the use of historic long-term meteorological data is proposed.

Methods

Cannonsville Reservoir

Cannonsville Reservoir is a dimictic impoundment owned by New York City (NYC) and located approximately 190 km northwest of the city. The reservoir serves as a water supply and to augment flow in the Delaware River downstream of the reservoir. It has a capacity of 3.73×10^8 m^3, a mean depth of 19 m when full, and a rather high average flushing rate of 2.6 y^{-1} (Owens et al. 1998). The reservoir has been in operation since 1966.

Water leaves the reservoir by one of three pathways,

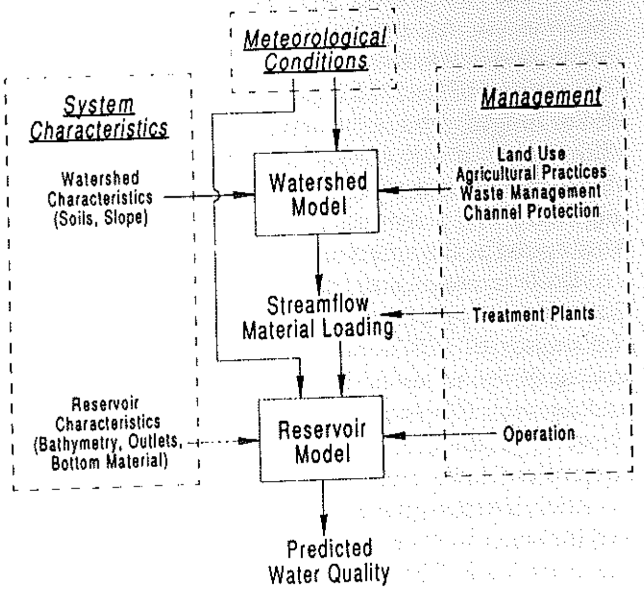

Figure 1.–Schematic of operation of linked watershed-reservoir models that accounts for impact of meteorological conditions and alternative management plans.

flow over the spillway, withdrawals for drinking water, and releases at the base of the dam. Drinking water can be withdrawn from depths of 10, 20 or 37 m below the spillway crest, with the middle intake most commonly used. The West Branch of the Delaware River (WBDR) is the primary tributary, contributing approximately 80% of the inflow received by the reservoir (Owens et al. 1998) and an even greater fraction of the external loads of critical nutrients and sediment (Longabucco and Rafferty 1998).

Cannonsville Reservoir is the most eutrophic of NYC's 19 reservoirs (NYCDEP 1997), as exhibited by high concentrations of phytoplankton biomass, blooms of nuisance cyanobacteria, severe depletion of oxygen in the hypolimnion (Effler and Bader 1998), low clarity and high turbidity (Effler et al. 1998b).

Meteorological, Hydrologic, and Operational Data

Daily average meteorological data from National Weather Service (NWS) stations in and nearby the reservoir's watershed were used in the watershed model. Weighted averages of 18 precipitation stations and 4 air temperature stations were computed to determine a single precipitation and air temperature input to the watershed model for each day of simulation (Schneiderman et al. 1998). For the reservoir model, meteorological data collected at the NWS station at Binghamton, New York, located 64 km northwest of the reservoir, were used for the period 1971-94. Daily average wind speed, air temperature, dew point temperature, and cloud cover were computed from hourly observations. An on-site meteorological station was established in late 1994 and supplied the data for 1995. Comparison of the 1995 measurements at the reservoir and at Binghamton indicated that the only significant differences on a given day were for wind speed. As a result, the measured wind speed at Binghamton was adjusted using a regression equation to estimate the wind speed at the reservoir (Gelda et al. 1998).

Daily average streamflow data from a United Stations Geologic Survey (USGS) gauge located near the mouth of WBDR were used in calibration and testing of the watershed (Schneiderman et al. 1998) and reservoir (Owens 1998a, Doerr et al. 1998) models. However, in the model forecasting described here, all streamflows were simulated by the watershed model.

Daily average rates for the three reservoir outflows and the water surface elevation have been measured by the New York City Department of Environmental Protection (NYCDEP) since construction of the reservoir (Owens et al. 1998). The multiple uses of the reservoir and variations in runoff common to the region result in strong seasonal and interannual variations in the hydrology of the reservoir (Owens et al. 1998). A hydrologic budget analysis supported the general accuracy of these measurements of reservoir outflows (Owens et al. 1998).

Models

The Generalized Watershed Loading Function (GWLF) model was used to simulate streamflow and nutrient and sediment loading from the watershed. GWLF has been documented by Haith and coworkers (Haith and Tubbs 1981, Delwiche and Haith 1983, Haith 1985, Haith and Shoemaker 1987). The model has two major submodels: a water balance model that simulates streamflow and its components (e.g., surface runoff and groundwater discharge, and a water quality model that utilizes the computed surface and subsurface runoff along with export coefficients to simulate the export of nutrients and sediment from the basin. The hydrologic submodel has a mechanistic basis, while the material loading submodel is empirical. Inputs for GWLF include landuse, selected soil properties, watershed elevation and slope, daily precipitation and air temperature, and empirical coefficients describing vegetative cover, dissolved nutrient concentrations in surface runoff and groundwater, nutrient accumulation rates for urban areas, nutrient concentrations in watershed soils, erosion, and sediment delivery. GWLF has been successfully calibrated for the WBDR basin (Schneiderman et al. 1998). Model streamflow simulations were compared to USGS measurements; phosphorus loads compared well to monitoring data which included runoff event-based sampling (Longabucco and Rafferty 1998). GWLF generates daily average streamflows and monthly average material loads.

A one-dimensional multilayer hydrothermal model has been successfully tested for Cannonsville Reservoir for the continuous period 1988 through 1995 (Owens 1998a), an interval during which major interannual variations in runoff and coupled features of reservoir operation occurred. The model accurately simulates important features of the reservoir's stratification/mixing regime, including depth of the thermocline, rate of hypolimnetic heating, temperatures of the epilimnion and hypolimnion, and duration of stratification (Owens 1998a). Meteorological data are used to simulate short and long-wave radiation, and evaporative and conductive heat transfer at the water surface. Mixing in the epilimnion is driven by wind, and is enhanced or damped by water surface cooling or heating, respectively. Mixing in the hypolimnion is also driven by surface wind shear, and is damped by stable stratification. Forcing conditions include streamflow rate and temperature, and reservoir operation. A number of hydrologic and hydrothermal measurements and calculations were made for Cannonsville Reservoir (Owens 1998b, c) which supported the development and testing of the hydrothermal model.

A dynamic one-dimensional nutrient-phytoplankton (eutrophication) model has been developed and successfully tested for the lacustrine zone of Cannonsville Reservoir (Doerr et al. 1998). The hydrothermal model described above (Owens 1998a) is the transport/mixing framework for this water quality model and provides prediction of water temperature. The nutrient-phytoplankton model has submodels for chlorophyll (chl), phosphorus (P), nitrogen (N), dissolved oxygen, and zooplankton that describe source and sink processes for each of these constituents. Model development and testing were supported by: (1) detailed measurements for forcing conditions, including material loads (Longabucco and Rafferty 1998), and meteorological conditions; (2) a temporally and spatially intensive monitoring program for model state variables (Effler and Bader 1998); and (3) process/kinetic studies to determine system-specific model coefficients related to deposition (Effler and Brooks 1998), sediment-water exchange rates (Erickson and Auer 1998), phytoplankton kinetics (Auer and Forrer 1998), relative contributions of phytoplankton and tripton in regulating light penetration (Effler et al. 1998a) and the availability of particulate P received as external loading to support phytoplankton growth (Auer et al. 1998). The credibility of the model was enhanced by this independent determination of important model coefficients, which greatly constrained the calibration process by reducing the number of coefficients subject to variation (Doerr et al. 1998). Hindcasting of historical conditions has established the accuracy of the watershed (Schneiderman et al. 1998) and reservoir (Owens 1998a, Doerr et al. 1998) models.

Forecasting Strategy

The basis for all model forecasts is a long-term continuous record of meteorological conditions. In the simulations presented here, the historical meteorological record from the various sites described above for the 25-year period from 1971-95 was used. This period was selected because meteorological data from all stations used in operation of the watershed and reservoir models were available. Also, this period covers most of the actual period of operation of Cannonsville Reservoir, as filling of the reservoir began in 1966. In addition, this period contains a range of wet and dry periods, including the flood of record in this region occurring in June 1972. A similar approach has been used to resolve the relative impacts of meteorological variability and anthropogenic effects on the stratification regimes of lakes with hydrothermal models (Effler and Owens 1986, Owens and Effler 1989).

Based on this 25-year record, a baseline condition was established for each of the three areas of water quality management affecting eutrophication, these being: (1) point source control of nutrients; (2) nonpoint source control of runoff and nutrients; and (3) reservoir operations. The baseline condition for point source loading was the average monthly loadings of P and N from the eight wastewater treatment plants in the watershed measured during 1996. The nonpoint source loading was based on watershed model (GWLF) simulations using existing land use, agricultural and waste management practices as identified from review of existing reports, remote sensing, and site visits (Schneiderman et al. 1998). For reservoir operations, the baseline condition was the actual historical operation for the period 1971-95. Specifically, these historical conditions are defined by the daily average flow rates for the release at the dam to WBDR, and the withdrawal rate for each of the three drinking water intakes. Spillway flow was computed by the reservoir model based on the simulated reservoir water surface elevation and a spillway rating curve (Owens 1998a). The baseline model simulation is thus a continuous prediction of the watershed and reservoir models for 25 consecutive years. All other simulations are based on the same 25 consecutive years of meteorological data, but with changes in streamflow, material loading, or reservoir operations as specified by specific management proposals or scenarios.

For the purpose of demonstrating the application of this strategy to potential management proposals, five additional simulations were performed, two related to reservoir operation and three related to reduction in nutrient loading. The "Full Reservoir" proposal involved adopting an operating rule whereby all drinking water withdrawals are set to zero, and dam release is set equal to the reservoir inflow up to a maximum of 200 million gal · day^{1} (8.8 m^{3}·sec^{-1}). When inflow exceeds this level, the additional water flows over the spillway, thus maintaining a full reservoir. This is a simple example of a reservoir operating policy or rule (Yeh 1985) whereby reservoir outflows are determined from a set of known characteristics of the inflows and reservoir. The second operation proposal, designated "Spring Release," involves increasing the dam release during the months of March, April, and May to a constant 200 million gal · day^{1} (8.8 m^{3} · sec^{-1}), a time when historical dam release is quite small (<10 million gal · day^{1}). This is intended to investigate the effectiveness of flushing water out of the reservoir that has been enriched in nutrients from spring runoff, before the onset of the summer growing season. Each of these two reservoir operation scenarios was investigated with watershed inflow and material loading set to baseline conditions.

A point source nutrient management plan was evaluated that involved reducing TP concentrations in treatment plant effluents to levels specified in a recent intergovernmental agreement (Table 1). A second nutrient management plan considered the implementation of agricultural "best management practices" (BMPs) for reduction of P export from farms within the watershed. This proposal accounts for potential reductions in nonpoint loading of P resulting from: (1) improvements in management of crops (reduction in corn acreage by 3.2%, implementation of strip cropping for an additional 15% of the remaining corn acreage); (2) reduction in P content of animal feed that results in a 22% reduction in P content of manure; (3) reductions in inputs from manure resulting from elimination of spreading on snow and use of hydrologically-inactive fields for preferential spreading; and (4) reductions in barnyard runoff by 33% through improved stormwater management. A third nutrient management proposal combined the point and nonpoint source management plan described above. These nutrient loading scenarios were simulated with reservoir operations set to the baseline conditions.

Results of simulations are presented here as selected summary statistics that represent salient ecological and water quality aspects of the predictions. The two reservoir operation proposals resulted in changes to the thermal stratification regime of the reservoir. Features of stratification presented here to characterize individual years within the multiple-year simulations are the duration of stratification (t_S), average (June-August) depth of the thermocline (z_{TH}), and the average (volume-weighted) temperature of the hypolimnion in August (T_H). Protocols for calculating these characteristics from the more detailed temperature simulations are described by Owens (1998a). All of the proposals investigated here result in changes in the predicted reservoir water quality from the baseline conditions. The quantitative indicator of trophic state adopted here is the summer (May-September) average concentration of total chlorophyll (chl, $\mu g \cdot L^{-1}$) in the upper mixed layer (epilimnion). The two other widely used indicators, Secchi disc transparency and total phosphorus (TP) concentration, have not been adopted because they are compromised in Cannonsville Reservoir by substantial contributions of resuspended sediment (Effler and Bader 1998, Effler et al. 1998a). Further, the nutrient-phytoplankton model for Cannonsville Reservoir (Doerr et al. 1998) does not presently simulate the resuspension process. An important feature that influences the occurrence of nuisance blooms of filamentous cyanobacteria is the relative availability of N and P, often represented by ratios of various forms of these nutrients (Rhee and Gotham 1980, Morris and Lewis 1988, Hecky et al. 1993). Decreases in the relative availability of N versus P (reductions in the N:P ratio) have been associated with a shift to these nuisance phytoplankton (Schindler 1977). The ratio of fixed inorganic nitrogen (FIN, the sum of total ammonia, nitrate, and nitrite) to total dissolved phosphorus (TDP) (Effler and Bader 1998, Morris and Lewis 1988) has been adopted in this analysis to characterize the potential shift to nuisance phytoplankton. Analysis of monitoring data (Effler and Bader 1998) and modeling results (Doerr et al. 1998) indicates the conditions favorable for the proliferation of nuisance cyanobacteria are FIN/TDP $< 24\ \mu gN/\mu gP$.

Table 1.–Concentrations of TP in wastewater treatment plant effluents to be achieved, as set forth in the NYC Watersheds Memorandum of Agreement.

Range of Treatment Plant Flow Q, $gal \cdot day^{-1}$	Effluent TP Concentration, $mg \cdot L^{-1}$
$Q < 50{,}000$	1.0
$50{,}000 < Q < 150{,}000$	0.5
$Q > 150{,}000$	0.2

Results and Discussion

External Loading

The focus of P loading reduction is the dissolved portion as this fraction largely drives primary production in the reservoir (Doerr et al. 1998). The point source management scenario is predicted to result in an average reduction of about 10% in the annual TDP load (Table 2). However, the average load for the critical summer (June-September) interval would decrease nearly 30% (Table 2). The average annual reduction in the TDP load would be greater for the nonpoint scenario (12%), but would be substantially less than the point source scenario during summer (2%, Table 2). A reduction of 23% in the annual average TDP load is predicted for the case of combining the point and nonpoint scenarios (Table 2). The predicted reduction in average annual total dissolved N loading for the nonpoint scenario is 8%.

Substantial interannual variability is predicted for baseline conditions as well as for each of the scenarios because of natural variations in meteorological and

Table 2.–Statistics (mean and coefficient of variation) of GWLF load estimates for 25 years for total dissolved P (TDP) and total dissolved N (TDN), for existing conditions and selected scenarios.

	Loads (kg·d^{-1})								
	TDP (annual)			TDP (June-Sept.)			TDN (annual)		
Scenario	Mean	cv	% reduct.	Mean	cv	% reduct.	Mean	cv	% reduct.
Baseline	47.4	0.21	–	22.8	0.32	–	1250	0.24	–
Point source	42.3	0.24	10.8	16.1	0.45	29.4	1250	0.24	–
Nonpoint source	41.7	0.20	12.0	22.3	0.31	2.2	1150	0.24	8.0
Combined point and nonpoint	36.6	0.22	22.8	15.6	0.44	31.6	1150	0.24	8.0

attendant hydrologic conditions (Table 2, Fig. 2). As a result, while reductions in loading occur in each individual year of the 25-year sequence, the loading during certain years following management is predicted to be greater than that occurring during other years without management (Fig. 2). Less overlap in the distributions of loads before and after management action exists in late summer (Fig. 3) for the point source scenario, partly because of the low flows that often occur during that period. These loading predictions suggest a rather detailed long-term monitoring program for WBDR (e.g., Longabucco and Rafferty 1998) would be necessary to resolve the benefits of such management actions on material loading to this reservoir.

Stratification/Mixing

Multiple-year simulations with the hydrothermal model for the full reservoir scenario depict (Table 3, Fig. 4a) the substantial impact that natural variations in meteorological conditions have on the stratification/mixing regime. These predictions are consistent with observations from long-term monitoring programs (e.g., Effler and Owens 1986) and model analyses conducted for other systems in the northeast (Effler

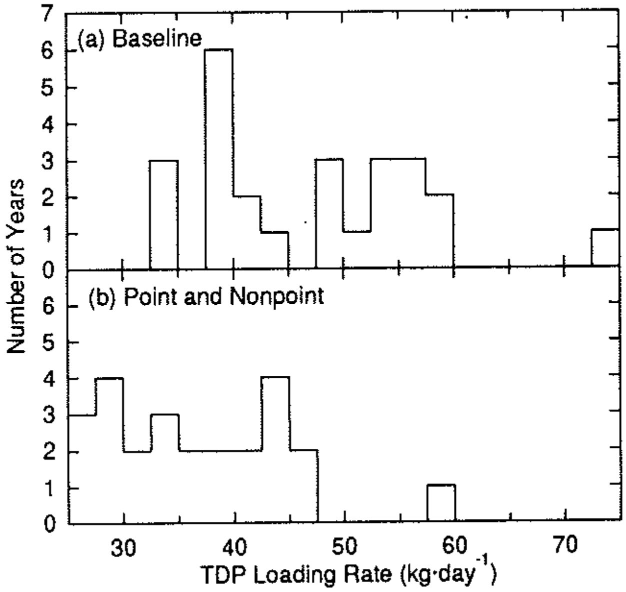

Figure 2.–Predicted (GWLF) distributions of annual average loading rate of TDP to Cannonsville Reservoir for 25 years of meteorological forcing conditions: a) baseline condition, and b) for scenario of point and nonpoint reductions in loads.

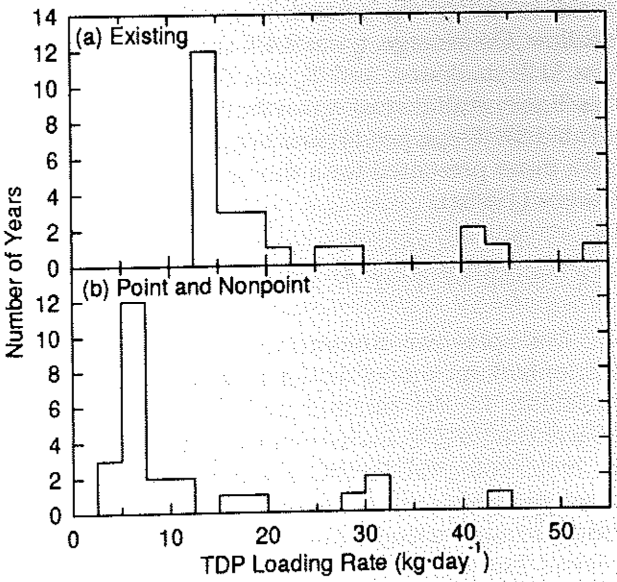

Figure 3.–Predicted (GWLF) distributions of average loading rate for the month of August of TDP to Cannonsville Reservoir for 25 years of meteorological forcing conditions: a) baseline condition, and b) for scenario of point and nonpoint reductions in loads.

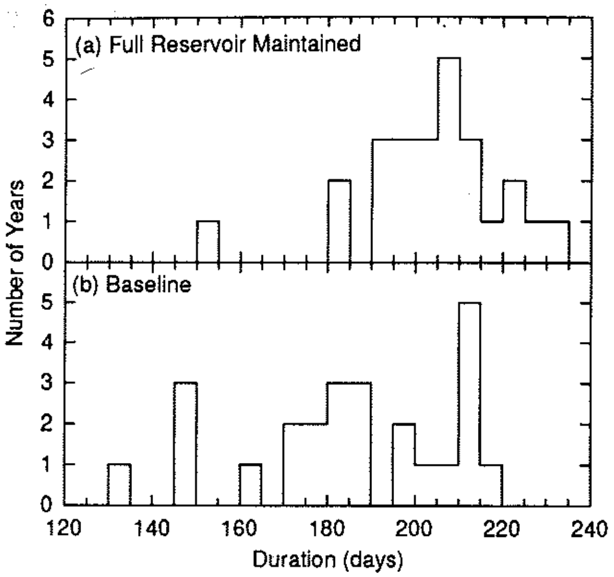

Figure 4.–Hydrothermal model predictions of distributions of the duration of stratification (t_s) in Cannonsville Reservoir for 25 years of meteorological forcing conditions: a) full-reservoir scenario, and b) baseline condition.

et al. 1996, Effler and Owens 1986, Owens and Effler 1989). The predicted variability is greatest for T_H and least for t_s (Table 3).

The variable drawdown of the reservoir (Owens et al. 1998) associated with operations, driven by natural seasonal and interannual variations in streamflow, augments the variability in features of the stratification/mixing regime attributable to meteorological variability (Fig. 4b, Table 3). Owens (1998a) found that drawdown tends to shorten t_s, increase T_H, and make z_{TH} more shallow. On average, t_s was 9.4% shorter (Fig. 4b), z_{TH} was 31% shallower, and T_H was 61% warmer for the baseline operations case versus the full reservoir scenario (Table 3). These predictions are generally consistent with those presented for a shorter (8-year) period by Owens (1998a).

Chlorophyll and N:P Ratio

Multiple-year simulations with the nutrient-phytoplankton model depict substantial interannual variability in the summer average epilimnetic chl concentration (Fig. 5a) in response to natural variations in meteorological forcing conditions, as mediated through variations in reservoir operation, flushing, external nutrient loading, and the stratification/mixing regime. The predicted mean for 25 years of simulations is 10.2 $\mu g \cdot L^{-1}$, somewhat lower than the measured average (14.5 $\mu g \cdot L^{-1}$, Effler and Bader 1998) for 14 years over the 1974-1996 interval. Reductions in point source loading over this interval (Longabucco and Rafferty 1998), and the lack of consideration of the internal source of P associated with resuspension (Doerr et al. 1998, Auer et al. 1998) likely contributed to this difference.

A shift to lower, (~30%) chl concentrations is predicted for the strictly hypothetical full reservoir scenario (Fig. 5b). This is consistent with the analysis of monitoring data that identified a tendency for higher chl in summers of greater drawdown, supporting the position that there is a water quality "cost" for the operation of the reservoir for its intended use (Effler and Bader 1998). Overlap in the distributions for the baseline operation (Fig. 5a) and full reservoir (Fig. 5b) cases is predicted because the reservoir has remained full in a number of years in response to high runoff (Owens et al. 1998) and other compensating effects. The spring release operation proposal is predicted to have only a very minor effect on the average epilimnetic summer concentration of chl in the reservoir (Fig. 5c).

Shifts to lower summer average chl concentrations are predicted for the management scenarios of reduced external phosphorus loading (Table 2, Fig. 5d-f). These analyses depict the importance of the timing of external loads with respect to summertime water quality in this reservoir. The benefit of point source control (Fig. 5d) is substantially greater than the nonpoint scenario (Fig. 5e) despite the smaller reduction in annual loading (Table 2). Most of the TDP load received by the reservoir from nonpoint sources occurs during high runoff intervals, particularly in spring (Longabucco and Rafferty 1998). However, much of the spring load is flushed from the reservoir before summer. In contrast, the point source inputs received during the summer, when the flushing rate is reduced (Owens et al. 1998), have a direct impact in supporting summertime phytoplankton growth. A reduction in the average epilimnetic summer chl concentration of 15% is predicted for the point source scenario (Fig. 6d). In contrast, the average reduction predicted for the nonpoint management scenario is <5%. The predicted effects of implementing both the point and nonpoint reductions are nearly additive, resulting in

Table 3.–Statistics of predicted features of the stratification regime of Cannonsville Reservoir for 25 years, for baseline and full reservoir scenarios.

Scenario	t_s(days)		z_{TH}(meters)		T_H(°C)	
	Mean	cv	Mean	cv	Mean	CV
Full-reservoir	203	0.08	6.5	0.11	6.6	0.14
Baseline	184	0.13	8.5	0.15	10.6	0.20

an average decrease of ~20% in the average summertime chl concentration.

The predicted variability in chl concentrations (Fig. 5) is important in establishing realistic expectations for the response of the reservoir to management actions. Substantial overlap with baseline conditions is predicted for all three phosphorus loading management scenarios. In other words, natural variations in meteorological conditions would result in summer average concentrations in certain years following loading reductions that equal or exceed values encountered prior to such reductions. Thus, evaluations of reservoir response to management actions based on comparison of single years before and after implementation is misleading and inappropriate. Long-term monitoring would be necessary to fairly resolve the extent to which systematic benefits are realized. Further, monitoring frequency must be adequate to accurately represent summertime conditions. The response predicted for the nonpoint scenario may be too small (Fig. 5a and e) to be resolved by practical monitoring programs.

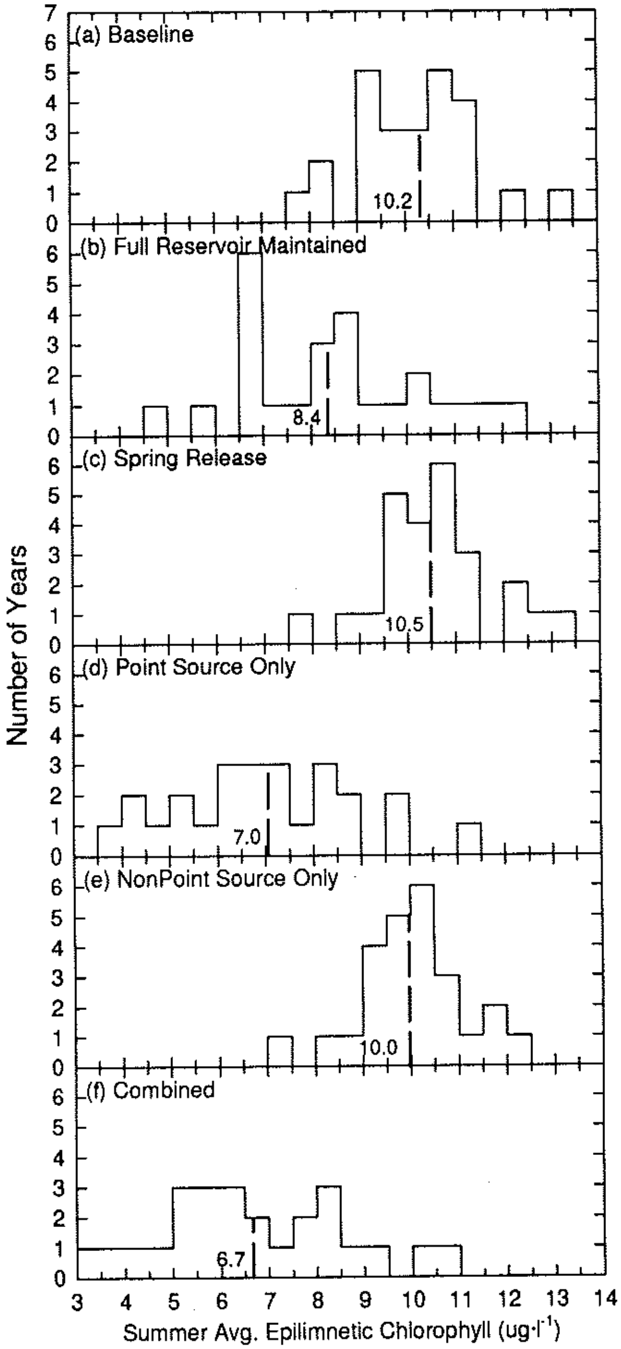

Figure 5.–Nutrient-phytoplankton model predictions of the distributions of epilimnetic summer average chlorophyll concentrations (chl) in Cannonsville Reservoir for 25 years of meteorological forcing conditions: a) baseline condition, b) full reservoir scenario, c) spring release scenario, d) point source phosphorus loading reduction scenario, e) nonpoint source nutrient loading reduction scenario, and f) combined point and nonpoint loading reduction scenario.

The time interval over which the epilimnetic N:P ratio is favorable to nuisance cyanobacteria (FIN:TDP<24) is predicted to decrease for each of the three scenarios of reduction in external phosphorus loading (Fig. 5d-f). These changes are linked to the reductions in phosphorus loading. The decreases suggest the duration of nuisance cyanobacteria dominance of the phytoplankton would become shorter (particularly for scenarios that include reductions in point source loading), consistent with observations reported for test systems in the literature (Schindler 1977). It may be desirable to further delimit these populations by considering the range of water temperature under which these forms of phytoplankton tend to prosper (Harris 1986, Reynolds 1984). Overlap in the N:P ratios for existing and scenario conditions is also predicted (Fig. 6), associated with natural variations in forcing conditions.

Summary and Conclusions

A modeling strategy that includes three tested models (Schneiderman et al. 1998, Owens 1998a, Doerr et al. 1998) and long-term meteorological data for Cannonsville Reservoir, has been used to demonstrate the wide variations to be expected in nutrient loading, reservoir stratification, and summer average epilimnetic concentrations of chl in response to natural variations in meteorological conditions. This strategy yields predictions that have been presented in the format of distributions of the frequency of occurrence of selected statistics that represent salient ecological and water quality aspects of the predictions. This approach creates a more realistic picture of ecosystem response and behavior when compared to the use of critical environmental conditions of shorter duration. Predictions of variability in chlorophyll concentrations were similar to those observed in long-term monitoring data for the reservoir.

The choice of the 25-year period of 1971-95 was largely based on the availability of meteorological data from the various stations used. As more meteorological data becomes available, it may be added to this continuous record. As the number of years considered in the analysis is increased, this can only enhance the realistic range of meteorological conditions and thus the extent to which the model predictions represent the entire range of reservoir water quality conditions that might occur. Alternatively, if an artificial or synthetic time series of meteorological data is generated by some means, this could also be used as the basis for analysis of management alternatives. However, a technique for generating a synthetic long-term time series of multiple meteorological quantities has not been described in the literature.

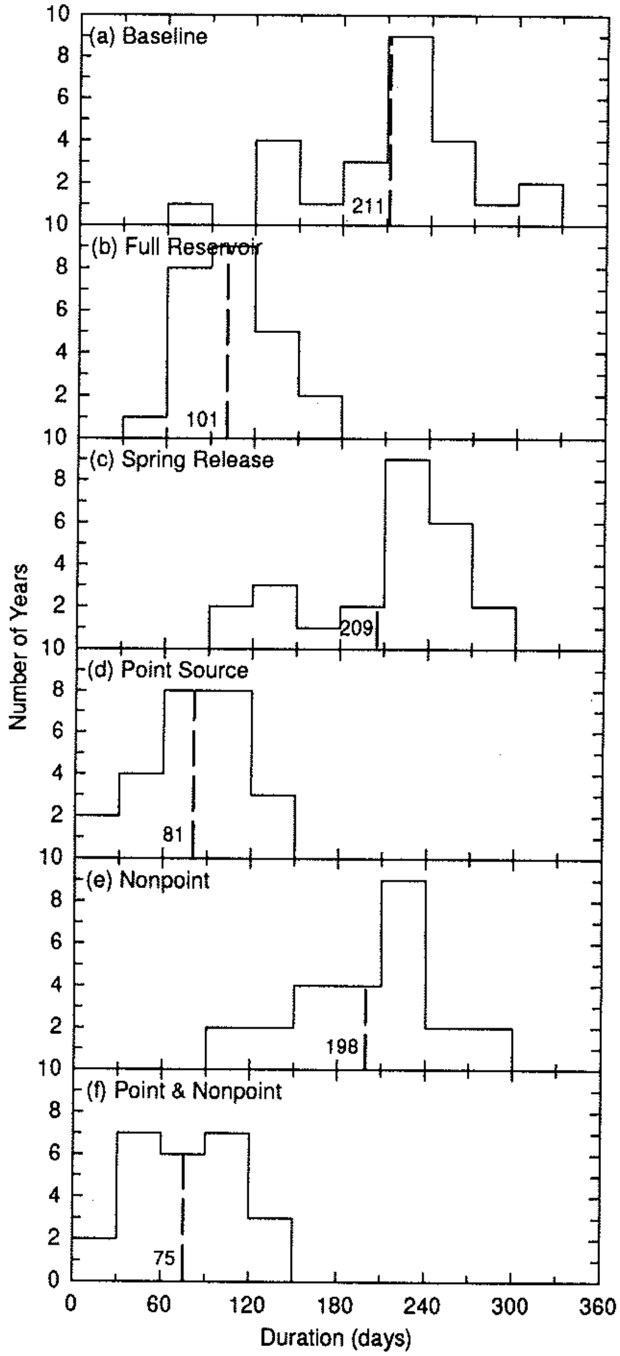

Figure 6.–Nutrient-phytoplankton model predictions of the distributions of the time period for which the ratio FIN:TDP<24 in Cannonsville Reservoir for 25 years of meteorological forcing conditions: a) baseline condition, b) full reservoir scenario, c) spring release scenario, d) point source phosphorus loading reduction scenario, e) nonpoint source nutrient loading reduction scenario, and f) combined point and nonpoint loading reduction scenario.

The modeling strategy or framework has been applied for several management scenarios for the reservoir. These particular scenarios were selected to demonstrate the strategy for model forecasting, particularly the presentation and interpretation of the model simulations. The proposal for point source loading reduction is of significant interest in that owners of treatment plants in the watershed have committed to meeting specific effluent limitations (Table 1). There are a wide range of other management proposals involving nonpoint sources and reservoir operations that have not been specifically considered here, but may be considered in the future within the framework described here. Some scenarios may be unrealistic in terms of the practical requirements and constraints imposed on managers. For example, maintaining the reservoir at its full storage capacity is certainly unrealistic and probably not desirable. However, the model predictions for such cases provide insight into the effect of operations on reservoir water quality.

Nonetheless, some preliminary conclusions may be made regarding the relative impact of point and nonpoint source controls, and of reservoir operations. Model simulations have demonstrated that drawdown of the reservoir tends to decrease the duration of stratification (t_s), increase hypolimnetic temperatures, and increase epilimnetic chl concentrations. The particular nonpoint source management scenario considered here results in reduction of phosphorus loading during high runoff periods (particularly in spring), while point source reductions occur throughout the year. The benefit of point source control in reducing summer average chl was predicted to be substantially greater than nonpoint reductions because of the difference in the timing of these inputs. Nonpoint source management which focuses on reduction of summer nutrient loads may yield greater water quality benefit in years with significant summer streamflow.

In general, substantial overlap in the frequency distributions for phosphorus loading, features of stratification, and summer average epilimnion chl concentrations is predicted to occur before and after these management actions due to the effects of natural meteorological variability. Thus, evaluations of the reservoir's response to management actions should be based on continued long-term monitoring, not on comparison of one or two years before and after implementation. The modeling strategy described here should be used in evaluation of management options for this reservoir. Consideration of the effects of natural variations in meteorological forcing conditions provides a realistic representation of the response to be expected and the inherent variability. This modeling strategy is presently under development for other reservoirs in NYC's water supply system.

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