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Application of a steady-state nutrient model and inferences for load reduction strategy in two public water supply reservoirs in eastern Connecticut

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Abstract

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Mansfield Hollow Lake (MHL) and Willimantic Reservoir (WR) are two reservoir lakes located in eastern Connecticut in the northeastern United States. MHL formed behind the Mansfield Hollow Dam constructed by the U.S. Army Corps of Engineers in 1952 and is primarily fed by the Fenton, Mount Hope and Natchaug Rivers. The WR lies approximately 1-km downstream from the Mansfield Hollow Dam. Total dissolved nitrogen, phosphorus and chlorophyll *a* measurements indicate the water bodies could be classified as borderline mesotrophic/eutrophic. A steady-state numerical software package (Bathtub) designed to facilitate application of empirical eutrophication models to morphometrically complex reservoirs was used to determine the trophic status in MHL and WR based on different phosphorus and nitrogen loading budgets.

The short hydraulic residence times and rapid flushing rates in MHL and WR are directly related to the flow rates in the streams discharging into MHL. The low flow period could significantly increase the hydraulic residence times of these two reservoirs. Therefore, the sampling design emphasized periods of low flow in late August and early September to assess the impact of nutrient inputs to MHL and WR during dry periods. The results of a low flow sampling period (August 2002) were used to calibrate and test the Bathtub model developed for these water bodies.

Application of the Bathtub model to differing flow regimes, notably average flows, suggested that nitrogen or phosphorus could limit the productivity and cause eutrophication in the two lakes. Results of this study indicated that the Bathtub model could be used to predict total nitrogen and total phosphorus concentrations with reasonable accuracy, but it might not be a suitable tool for predicting organic nitrogen or algae in rapidly flushing lake systems. To further investigate and validate the assumptions made in this study, more sampling data are needed, especially during high intensity storm events to investigate possible sources of nutrient flow into the two lake system and further calibrate the Bathtub model for the MHL-WR watershed.

Key Words: Bathtub, eutrophication, lakes, nutrients, streams, water quality

Table 1.-Watershed Coverage by the Fenton, Mount Hope, and Natchaug rivers.

Total watershed area	412 sq. km [159 square miles (100%)]
Fenton River	88 sq. km [34 square miles (22%)]
Mount Hope River	96 sq. km [37 square miles (23%)]
Natchaug River	228 sq. km [88 square miles (55%)]

Mansfield Hollow Lake (MHL) and Willimantic Reservoir (WR) are located in Tolland County in northeastern Connecticut within the Thames River Basin (Fig. 1). Construction of the Windham Reservoir Dam and its corresponding pump house in 1885 resulted in the creation of WR, and building of the Mansfield Hollow flood control dam by the U.S. Army Corps of Engineers (USACE) in 1952 resulted in the formation of MHL (also known as Naubesatuck Lake). The three main tributaries of MHL are Fenton, Natchaug and Mount Hope rivers, with a total watershed area of 412 km^2 (159 mi^2). The outlet located at the bottom of MHL discharges to Natchaug River, which continues south into WR. The water stage at this outlet was arbitrarily set as the datum, and all vertical measurements are measured relative to this datum. A water treatment facility at WR treats and distributes an average of 9,464 m^3 (2.5 million gallons) of water per day as potable water to areas of Windham and Mansfield by the Windham Water Works (Hoag 2003). Because the WR is a source of potable water, maintaining the water quality in the reservoir is essential.

To estimate the potential response of these two impoundments to nutrient reductions, a mass balance model was developed and calibrated to the measured data using the Bathtub software (Walker 1999). The Bathtub model error analysis capability was used to evaluate the model's prediction uncertainties, based on variance estimates for all input data. The Bathtub model predictions are useful to determine the maximum nutrient loadings needed to maintain chlorophyll *a* and nitrogen concentrations at acceptable levels for potable water supply. The measured parameters were compared against the Bathtub model simulation results to examine the prediction capabilities of the Bathtub model and its reliability as a management tool for water authorities.

Watershed characteristics of Mansfield Hollow Lake and Willimantic Reservoir

Land use

Typical mixed northeastern hardwood forests of northeastern North America combined with agriculture and suburban development form the dominant land uses in these watersheds. The urbanized areas associated with the University of Connecticut campus and the local town's commercial districts are the only substantial urban coverage in the watershed and comprise a small fraction of the MHL watershed area. As a designated Public Water Supply Watershed, permitted point source discharges are prohibited in the watershed by the Connecticut Department of Environmental Protection (CTDEP) under Section 22a-417 (CTDEP 2005). Therefore, the sources of nutrient loading to MHL and WR are primarily from nonpoint sources.

Surface water classification

The CTDEP classified MHL, WR, and the three tributaries (Fenton, Mount Hope, and Natchaug rivers) that discharge into these reservoirs as class B/AA under its water quality classification, indicating that the water quality condition was class B, but the achievement goal was Class AA. Class B surface waters are designated for fish and other aquatic life and wildlife, recreation, navigation, industrial and agricultural water supply. Class B surface waters must be treated before use as drinking water (CTDEP 2002). Class AA surface waters are designated for existing or proposed drinking water supplies and other designated uses of Class B surface waters described above. The basis for the B/AA classification of this system was the presence of old landfills located in the upper, and some lower, reaches of the drainage basin with the potential to leach contaminants into the reservoirs.

The watershed includes three major basins (Table 1): The Natchaug River, which makes up a majority of the watershed, the Fenton and Mount Hope rivers, which comprise the remainder. MHL has a surface area of 182 ha (450 ac) with a capacity of 3.454×10^6 m^3 (2,800 acre-ft) at an average summer pool depth of 1.9 m (6.2 ft), reaching a maximum depth of approximately 4.9 m (16 ft). The concrete dam can maintain a maximum water depth of 15.5 m (51 ft) at the spillway (USACE 2000). MHL can reach a maximum pool area of 761 ha (1,880 ac) with a capacity of 60.69×10^6 m^3 (49,200 acre-ft). When full, the outflow capacity of the spillway gate in MHL is 288 m^3 s^{-1} or 10,200 cfs (USACE 2000).

MHL is the larger of the two impoundments and has a high flushing rate. Distribution of residence times in MHL is approximately log-normal with a mean of 12.8 days and a standard deviation of 12 days (Nadim *et al.* 2005). The average hydraulic loading rate (*i.e.*, total annual runoff into MHL divided by the surface area of MHL at normal summer pool elevation) into MHL is 13 m yr^{-1}. For MHL, the total watershed area of 41,200 ha and lake surface area at average pool elevation of 182 ha gives a ratio of 226. A high ratio of watershed to lake surface area is common to river impoundments and contributes to the fast flushing rate in this system (Wetzel 2001).

in contaminants. Sampling personnel were required to wear clean, powder-free rubber gloves. All samples collected in the field were placed inside transportable coolers, brought to the laboratory and kept in a walk-in cooler pending analysis.

To investigate the impact of storm flows on water quality in the inflowing tributaries, automated ISCO® samplers (Teledyne ISCO, Inc., Lincoln, Neb.) were used to take samples every three hours for a period of three days following a moderate rain storm (3-4 cm in 72 hrs) that occurred September 3-5, 2002.

Model description

The Bathtub model is computer software designed to facilitate application of empirical eutrophication models to morphometrically complex reservoirs (Walker 1999). The numerical code performs water and nutrient balance calculations in a steady-state, spatially segmented hydraulic network that accounts for advective transport, diffusive transport, and nutrient sedimentation. Eutrophication-related water quality conditions (expressed in terms of total phosphorus, total nitrogen, chlorophyll *a*, transparency, organic nitrogen, ortho-phosphorus, and hypolimnetic oxygen depletion rate) are predicted using empirical relationships previously developed and tested for reservoir applications (Walker 1985).

By applying the appropriate spatially segmented scheme of the six available schemes in the Bathtub model, the model can be applied to a wide range of reservoir configurations. External inflows are specified as tributaries for any model segment. Outflow from each segment discharges to the next downstream segment or out of the system (Walker 1999). The Bathtub model formulates water and nutrient balances by evaluating the following terms for each segment:

$$\text{Water Inflows} = \text{Water Outflows} + \text{Increase-in-Storage} + \text{Net Evaporative Loss} \tag{1a}$$

$$\text{Nutrient Inflows} = \text{Nutrient Outflow} + \text{Advective Fluxes} + \text{Diffusive Fluxes} + \text{Atmospheric Deposition of Nutrients} \tag{1b}$$

The mass balance relations are defined as a system of simultaneous nonlinear equations that are solved iteratively by Newton's method (Burden *et al.* 1981). Water-balance calculations are the basis for derivation of advective terms and are expressed as a system of simultaneous linear equations. Matrix inversion is applied to calculate the advective outflow from each model segment. Diffusive transport terms represent eddy diffusion and apply to simulation of spatial variations within reservoirs (Walker 1999).

Table 2.-Water sampling depths in MHL and WR (sampling was conducted on September 11, 12, 16, 17, and 18, 2001).

Mansfield Hollow Lake	**Water Sampling Depth (measured from surface of the water)**
MHL-Upper Lake	0.3 m, 0.6 m, 1.2 m, and 1.5 m
MHL-Middle Lake1	0.6 m, 1.4 m, 2.2 m, and 3.0 m
MHL-Middle Lake2	0.6 m, 1.4 m, 2.2 m, and 3.0 m
Near Dam	0.3 m, 1.15 m, 1.8 m, and 2.55 m
Willimantic Reservoir	**Water Sampling Depth (measured from surface of the water)**
WR1	0.6 m, 1.5 m, 2.4 m, and 3.3 m
WR2	0.6 m, 1.5 m, 2.4 m, and 3.0 m

The Bathtub model provides the user with the option of choosing the suitable submodel for prediction of various water quality parameters. If the user decides not to choose a specific submodel for a parameter, then the Bathtub model assigns a default submodel for that parameter.

To apply the Bathtub model to a reservoir or lake system, a relatively small number of input parameters are required. We provided input data for total nitrogen, organic nitrogen, total phosphorus, and chlorophyll *a* for two dates during the September 2001 dry period and a rain storm event that occurred September of 2002 (Table 3). For concentrations of nutrients at each sampling location in MHL and WR, average concentration of the vertical samples with all depths receiving equal weights in the estimation of the average values were used. The Secchi depth of MHL in this study ranged from 1.65 to 1.7 m. Variances were estimated for all model input data and expressed as the coefficient of variation (CV) of the mean, following Walker (1987). Oxygen, pH, and temperature were measured at various depths at six cross-sections along MHL and WR (Fig. 2).

Indicator of limiting nutrient

In the Bathtub model, the following empirical relation is used to determine if nitrogen or phosphorus is the nutrient limiting trophic response of the reservoir:

$$(\text{Total N} - 150)/\text{Total P} \tag{2}$$

where N and P are in μg/L.

If the index value is low, namely $(N-150)/P < 10\text{-}12$, the system is considered nitrogen-limited, whereas if the index value is high, namely $(N-150)/P > 12\text{-}15$, the system is phosphorus-limited (Walker 1999).

Table 3.-Measured mean and standard deviation (STD) of concentrations of total phosphorus (μg/L), total nitrogen (μg/L), organic nitrogen (μg/L), and chlorophyll *a* (μg/L) during low flow and storm flow conditions.

	TN		Org-N		TP		CHL *a*	
	Storm Flow*	Low Flow**	Storm Flow	Low Flow	Storm Flow	Low Flow	Storm Flow	Low Flow
Fenton River								
Average	527.5	498.6	263.6	382.9	25.0	25.3	1.5	1.0
STD	90.4	151.7	66.5	76.3	11.7	11.3	0.7	0.7
Sample Size	24	8	24	8	24	8	24	8
Mount Hope River								
Average	568.3	430.3	273.4	331.5	19.8	44.7	1.2	2.2
STD	108.6	116.1	54.9	116.2	3.9	21.9	0.2	1.4
Sample Size	24	8	24	8	24	8	24	8
Natchaug River								
Average	453.8	322.0	255.8	219.5	16.1	40.9	0.9	3.3
STD	70.1	77.9	56.2	49.2	4.7	17.0	0.1	1.7
Sample Size	24	9	24	9	24	9	24	9

* Storm flow measurements were conducted in September of 2002

** Low flow measurements were conducted in September of 2001

Table 4.-Comparison between Bathtub model simulation results and August-2001 field data.

Sampling Location	TP		TN		Org-N		CHL *a*	
	Mean	Stnd. Error	Mean	Stnd. Error	Mean	Stnd. Error	Mean	Stnd. Error
MHL-UpperLake (predicted)	23.8	2.6	510.9	41.4	420.9	86.3	10.3	3.5
MHL-UpperLake (observed)	NA	NA	508.0	13.7	234.7	32.6	12.7	1.0
MHL-UpperLake1 (predicted)	23.6	2.7	508.2	42.1	418.2	84.9	10.2	3.4
MHL-UpperLake1 (observed)	28.3	6.8	506.7	50.7	188.0	3.8	12.9	2.5
MHL-UpperLake2 (predicted)	23.7	2.7	510.7	2.7	418.9	85.3	10.2	3.4
MHL-UpperLake2 (observed)	NA	NA	483.0	9.7	308.0	6.2	11.3	0.9
Near Dam (predicted)	23.4	2.7	507.0	42.9	348.6	65.1	7.1	2.8
Near Dam (observed)	NA	NA	589.0	100.1	123.0	12.3	12.0	1.4
WR1 (predicted)	23.3	2.7	504.7	43.1	504.7	43.1	10.0	3.4
WR1(observed)	NA	NA	NA	NA	387.0	16.3	9.7	0.1
WR2 (predicted)	23.3	2.7	504.0	43.2	414.7	84.2	10.0	3.4
WR2(observed)	NA	NA	NA	NA	NA	NA	NA	NA

Bathtub model application

The MHL and WR water bodies were considered as one reservoir with four segments and three tributaries in the Bathtub simulation scenario (Scheme 2 in the Bathtub model). During the calibration procedure, which employed low flow period measurements (average of week September 11-18, 2001), various modeling scenarios built in the program for prediction of total phosphorus, total nitrogen, and chlorophyll *a* estimations were tested, and submodels that showed the least discrepancies between the measured and estimated values were chosen.

The calibrated model was then tested with an independent set of data obtained during the week of August 19-23, 2001, field measurements. The measured and modeled estimated results were in reasonable agreement (Table 4). Note that sampling was not conducted in the entire project site during the August 2001 sampling campaign, and some parameters were not accounted for during this sampling period.

Atmospheric deposition of nitrogen and the Fenton River inflow to the reservoir (initially assumed equal to Mount Hope and subsequently estimated using an established correlation using Mount Hope flow data) were also incorporated in the calibration process. For the prediction of total nitrogen and total phosphorus concentrations in MHL and WR, the second-order Available-N and second-order Available-P models were found to be most suitable, respectively. For chlorophyll *a*, the P-Light-Flushing model was best representative of chlorophyll *a* concentration estimates (Walker 1999).

In this study, the Bathtub model was used to examine a number of different scenarios. Keeping all nutrient input parameters constant, the flow rate of tributaries was increased from the low flow period of September 2001 to the average flow rate of 2001 to investigate the effect of flow variation on the concentration of total phosphorus in MHL and WR. The effect of varying concentration of total phosphorus in MHL and WR on the chlorophyll *a* concentration was also estimated with the Bathtub model.

Tributary and atmospheric inputs

Mean flow estimates in 2001 for Mount Hope and Natchaug rivers were taken from U.S. Geological Survey data reporting daily stream flow (USGS 2005a, 2005b). Due to the lack of direct flow measurements in the Fenton River, the flow in this stream was estimated with the aid of a low flow regression curve developed for 2004 and 2005 correlating it to the flow in the Mount Hope River. A synthetic flow duration curve and hydrograph were developed for the Fenton River based on the Mount Hope data. This approach did not assume that the flows were equal, or even equal on a per area basis for the two rivers. Instead, the assumption was made that the

Table 5.-Bathtub model input parameters and observed phosphorus and chlorophyll-a concentrations.

Lake Segment	Segment Volume Dry Period (hm^3)	Segment Depth at Sampling Points Dry Period (m)	External Inflow Dry Period (hm^3)·yr^{-1}	External Inflow Average 2001 Flow (hm^3)·yr^{-1}	Observed P Conc. µg·L^{-1}	CHL *a* µg·L^{-1}
MHL-UpperLake	0.7	1.5	3.0	54.5	17.0	11.3
MHL-UpperLake1	1.4	3.0	3.4	54.8	17.8	7.6
MHL-UpperLake2	1.4	3.0	3.7	55.2	18.0	3.4
Near Dam	1.8	4.0	6.7	267.2	16.0	2.2
WR1	0.3	1.9	6.8	267.3	14.8	12.9
WR2	0.5	3.0	7.0	267.5	17.5	6.6

flows on the two rivers were occurring at the same exceedance level due to the proximity of the basins and similarity in climate and land use. Details of this approach can be found in Warner *et al.* (2005).

The average of 11 days of low flow (five days before and five days after the sampling date) was taken for each stream as the flow input into the model (Table 5). The mean concentrations of measured nutrients in the Fenton, Mount Hope, and Natchaug rivers during the same sampling period were used as tributary inputs. Atmospheric input of nitrogen to the watershed area was taken from a study aimed at estimation of nitrogen deposition in Connecticut (Nadim *et al.* 2001) and applied as a representative value over the MHL and WR water surface. During this study, eight sampling sites (four urban and four rural) were chosen to represent rural and urban sections of Connecticut. Weekly average atmospheric deposition flux of nitrogen measured from 1999 to 2001 at Voluntown, a rural site in eastern Connecticut approximately 35 km southeast of MHL and WR, was used in the Bathtub model. However, atmospheric deposition of phosphorus was not measured in the study conducted by Nadim *et al.* (2001).

Results and discussion

Stratification assessment

The temperature profiles of MHL indicated a lack of stratification at sampling locations B2, D2, and C2 (Fig. 4a). However, a sharp temperature decrease of almost 1°C took place at sampling location E4 in WR between the depths of 0.9-1.2m below the water surface (Fig. 4b). The pH profiles did not indicate any stratification at sampling locations MHL-MiddleLake2 and WR2 (Fig. 5a and b). The level of dissolved oxygen in WR2 location dropped from 7 mg/L at 0.3 m below the water surface to about 5.2 mg/L at the depth of 4.5 m (Fig. 5b). The measured total nitrogen concentrations at the depth of 3 m at MHL-NearDam and WR2 were 46% lower than the water column average (Fig. 6a and b). The total nitrogen decrease with depth could be the result of greater concentrations of phytoplankton in the shallower photic zone, resulting in higher total nitrogen concentrations in these regions. However, more investigation is needed to fully characterize this phenomenon.

The Bathtub model has been used as an effective tool for lake and reservoir water quality assessment and management, particularly where data are limited (PDEP 2003a, 2003b). Prior successful applications of the Bathtub software include Smeltzer and Quinn (1996) who used it to develop a phosphorus reduction strategy for Lake Champlain in Vermont and New York State. However, the focus of their study was on changing phosphorus concentrations within Lake Champlain, and they did not examine other parameters such as total nitrogen or chlorophyll *a* concentrations. Wang *et al.* (2005) studied the degradation of water quality in Cheney Reservoir in Kansas by employing the Bathtub model to predict nutrient inputs into the reservoir based on differing types of land use. Using the observed values, they calibrated the model and found no significant difference at 95% confidence level between the predicted and observed values of total phosphorus, total nitrogen, organic nitrogen and chlorophyll *a* (Wang *et al.* 2005).

Total nitrogen

The Bathtub model simulation results were consistent with measured data for total nitrogen concentrations at four sampling locations in MHL (Fig. 7). No noticeable difference was observed between total nitrogen concentrations during low flow and average flow conditions. Simulated concentrations for total nitrogen in WR sampling locations WR1 and WR2 for low flow conditions were 20% and 49% higher than the measured values, respectively (Fig. 7). The connection between MHL and WR is through a low level outlet located

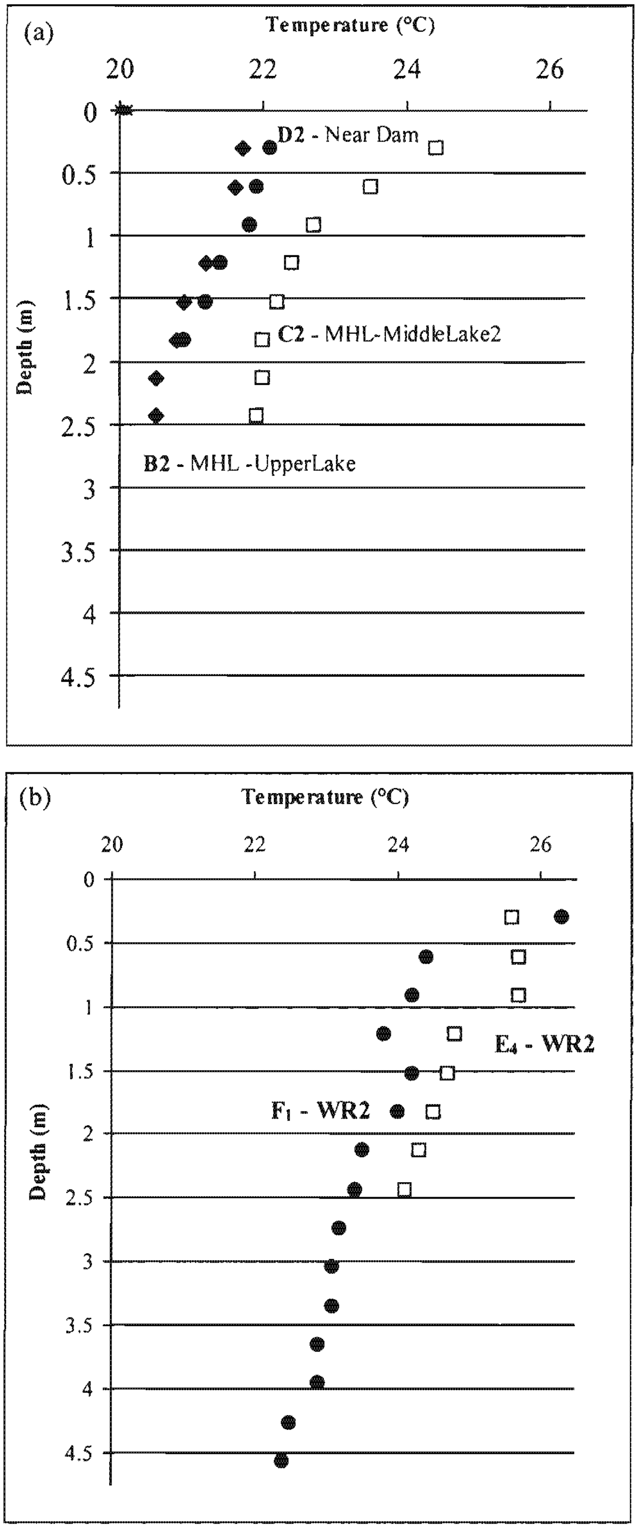

Figure 4.-Temperature profiles at (a) three sampling locations (B2, C2 and D2) in MHL at cross sections BB', CC', and DD'; and (b) two sampling locations (E4 and F1) in WR at cross sections EE' and FF' (see Fig. 2 for sampling locations) on September 18, 2001.

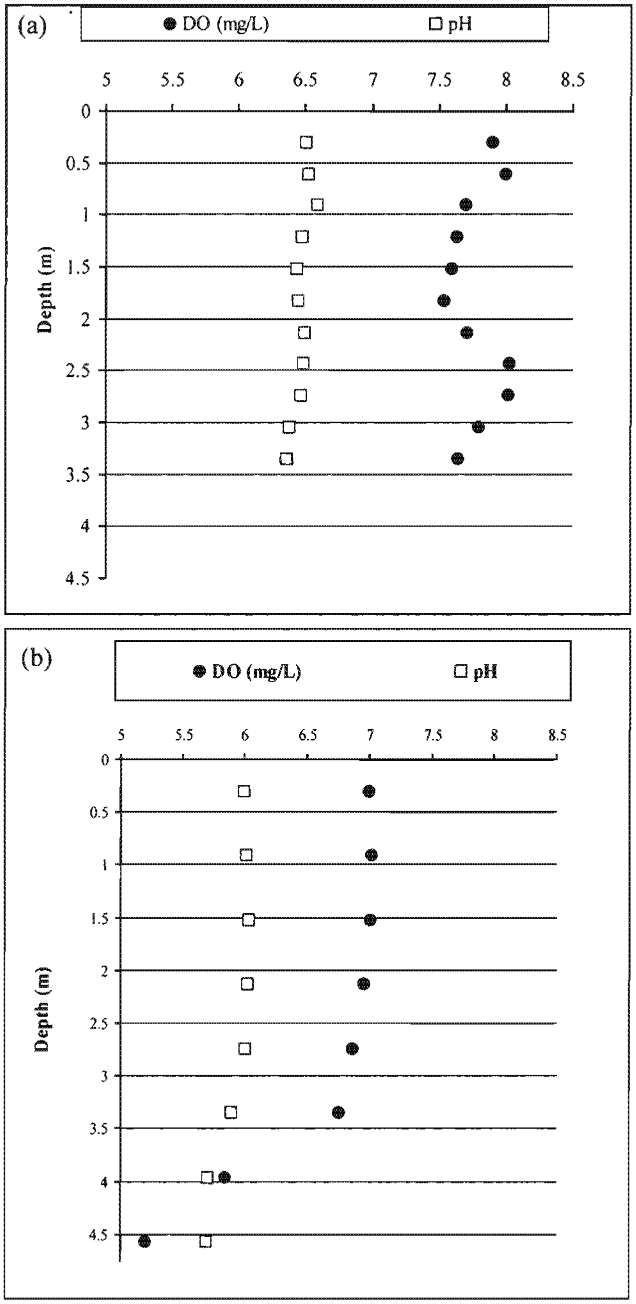

Figure 5.-pH and dissolved oxygen profiles in (a) MHL-MiddleLake2 and (b) WR2 (see Fig. 2 for sampling locations) on September 18, 2001.

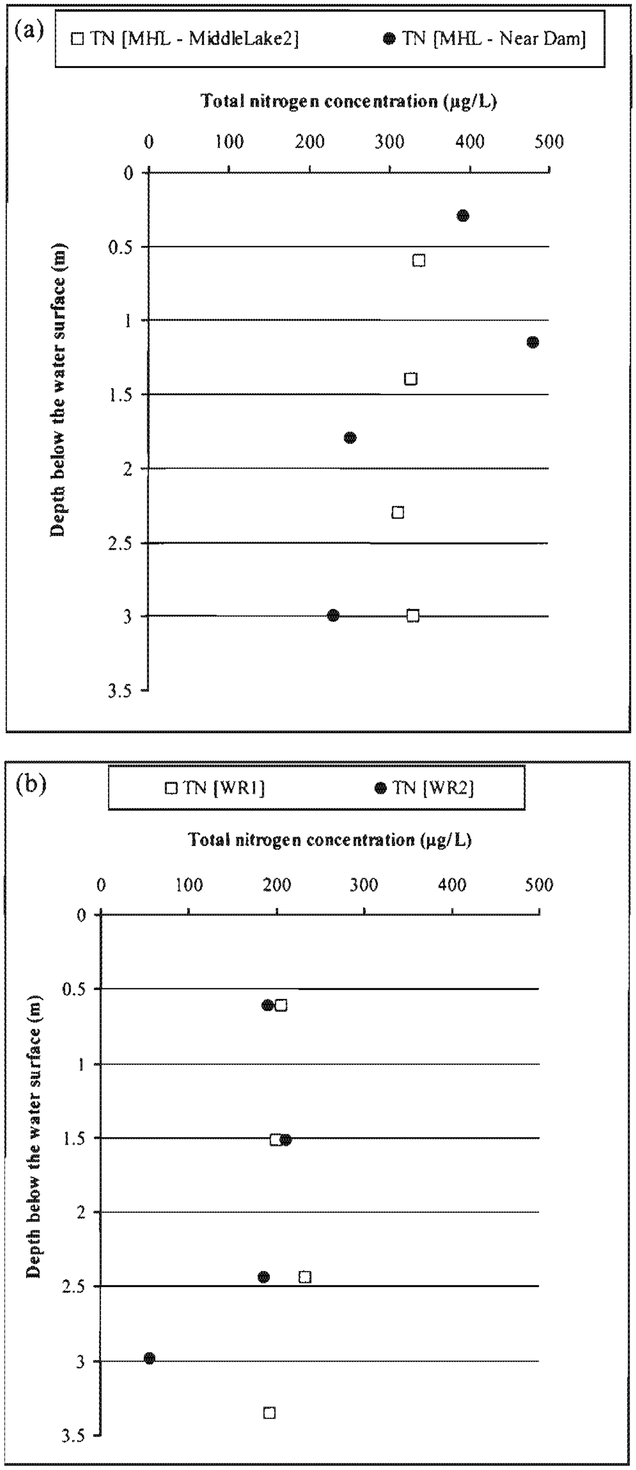

Figure 6.-Total nitrogen concentration profiles at sampling locations (a) MHL-MiddleLake2 and Near Dam, and (b) WR1 and WR2.

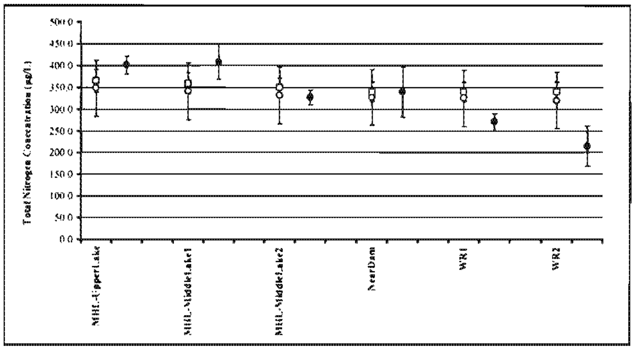

Figure 7.-Measured and Bathtub model estimated concentrations of total nitrogen in MHL and WR (●=measured, O=estimated with the Bathtub model using the low flow of September 2001, □=estimated with the Bathtub model using average flow rate of 2001). Note: low flow period measurements were used to calibrate the Bathtub model (error bars represent ± 1SE of the mean).

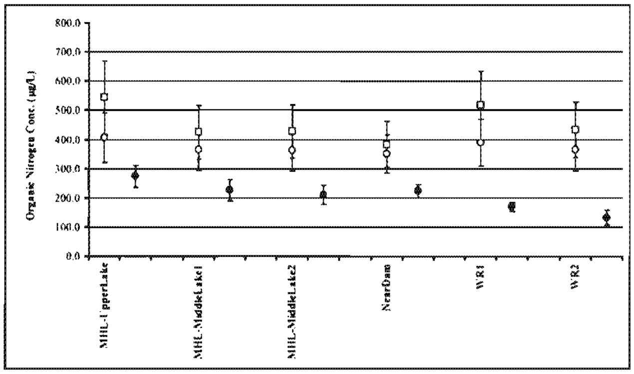

Figure 8.-Measured and the Bathtub model estimated concentrations of organic nitrogen in MHL and WR (●=measured, O=estimated with the Bathtub model using the low flow of September 2001, □=estimated with the Bathtub model using average flow rate of 2001). Note: low flow period measurements were used to calibrate the Bathtub model (error bars represent ± 1SE of the mean).

on the bottom of MHL. The total concentration of nitrogen measured at the Near Dam location dropped from about 400 µg/L at 0.3 m below the water surface to about 230 µg/L at the depth of 3 m (Fig. 6a). This shows that the total nitrogen being discharged to WR through the low level outlet of MHL was lower than the water column average at the Near Dam location in MHL and might explain the reduction of total nitrogen concentration in the bottom discharge from MHL to WR. At the WR2 sampling location the total concentration of nitrogen decreased from about 200 µg/L at 0.6 m below the water surface to 57 µg/L at the depth of 3 m (Fig. 6b).

Organic nitrogen

In contrast to the study of Wang *et al.* (2005), we were not able to obtain a reasonable match between the measured and simulated values for organic nitrogen. For MHL, Bathtub model estimates of organic nitrogen in the four sampling segments were 48-73% higher than the measured values (Fig. 8). For average flow conditions, the Bathtub model estimated values for organic nitrogen in MHL were 72-104% higher than measured. However, the Bathtub model predictions for low and average flows in WR ranged from 129 to 175% and 205 to 226% of measured values, respectively. Note that the approach to predict organic nitrogen in the Bathtub model was based on chlorophyll *a* concentration and Secchi depth. This relation was defined as:

$$N_{org} = 157 + 22.8b + 75.3a \qquad (3)$$

where b is chlorophyll *a* in mg·m^{-3}, and a is a measure of nonalgal turbidity given by an empirical relation (1/secchi (meters) - 0.25b).

This equation assumes significant contributions of organic nitrogen from the standing crop of algae, but an even larger portion can be derived from nonalgal particulate matter (as expressed by nonalgal turbidity) and a fixed "background" level. This prediction by the Bathtub model was not constrained by, or related to, the observed nitrogen concentration, so it is possible to obtain predicted values of organic nitrogen that are substantially higher than observed. Further, because the Bathtub model prediction of organic nitrogen was strongly coupled to the chlorophyll *a* concentration, the over-prediction of chlorophyll *a* (discussed in detail in the next section) resulted in an over-prediction of organic nitrogen. Moreover, because MHL and WR constitute a dynamic (fast flushing) system, the observed nitrogen data may not be representative of an equilibrium state assumed in the Bathtub model.

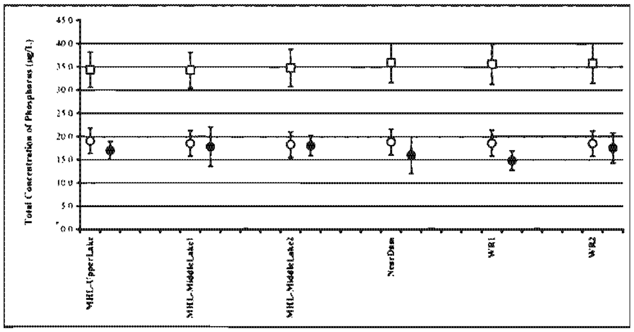

Figure 9.-Measured and the Bathtub model estimated concentrations of total phosphorus in MHL and WR (●=measured, O=estimated with the Bathtub model using low flow period of September 2001, □=estimated with the Bathtub model using average flow rate of 2001). Note: low flow period measurements were used to calibrate the Bathtub model (error bars represent ± 1SE of the mean).

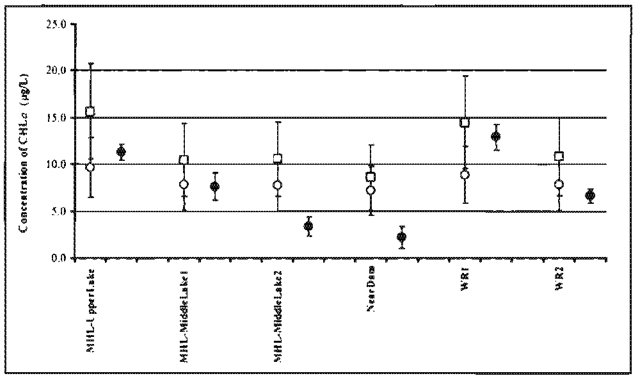

Figure 10.-Measured and the Bathtub model estimated concentrations of chlorophyll *a* in MHL and WR (●=measured, O=estimated with the Bathtub model using low flow period of September 2001, □=estimated with the Bathtub model using average flow rate of 2001). Note: low flow period measurements were used to calibrate the Bathtub model (error bars represent ± 1SE of the mean).

Total phosphorus and chlorophyll a

Phosphorus is often the limiting nutrient for aquatic plant growth and originates from apatite minerals, commercial fertilizers, manure, land irrigation with treated wastewater, nonagricultural fertilization, septic systems and industrial effluents (Stednick 2000). Chlorophyll *a* concentrations measured in the Fenton, Mount Hope and Natchaug rivers (0.9-3.25 µg/L) were 3-4 times lower than the values measured in MHL and WR (2.2-11.3; Tables 3 and 5). The hydraulic residence times in MHL and WR were 25-35 and 2-3 days, respectively, during the five sampling dates in September 2001 (Fig. 3). The short hydraulic residence times and rapid flushing rates in MHL and WR were important factors in determining acceptable phosphorus loading to these systems. In a study comparing the factors influencing phytoplankton abundance in rivers, lakes and impoundments, Soballe and Kimmel (1987) stated that aquatic systems were occupying positions along a continuum ordered by water residence time and the algal-phosphorus relationships of reservoirs were the intermediate phase between rivers and natural lakes Because eutrophication effects of total phosphorus in lakes generally tend to decrease at lower hydraulic residence time (Soballe and Threlkeld 1985), these two systems should be able to accept greater phosphorus loads than impoundments or lakes that have less flushing (*e.g.*, most natural lakes).

Phosphorus estimated by the Bathtub model was 2-20% higher than the measured total phosphorus concentrations at the six sampling locations in MHL and WR for low flow conditions (Fig. 9). However, note that for average flow conditions (keeping other parameters constant) the Bathtub model estimated 100% higher concentrations than the observed measurements. There was reasonably high agreement

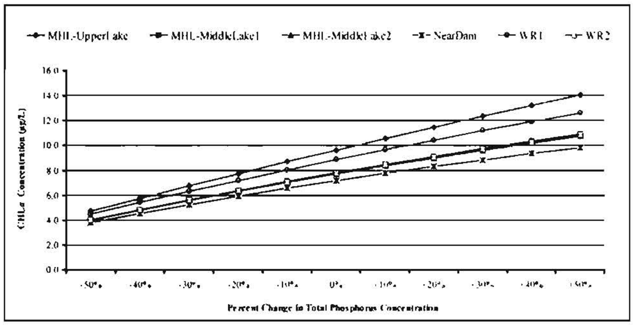

Figure 11.-Effects of changes in total phosphorus concentration in the inflows to MHL and WR (range ± 50%) on chlorophyll *a* concentration as estimated with the Bathtub model.

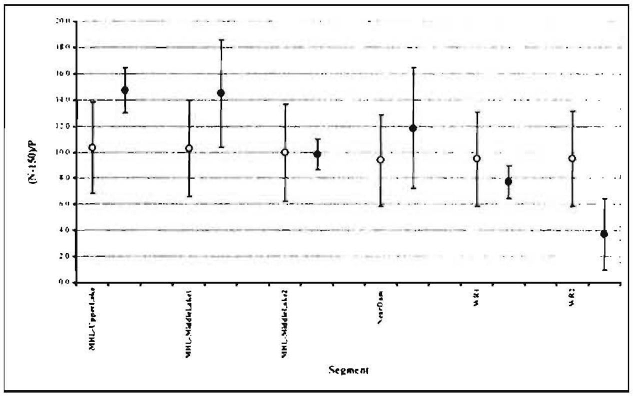

Figure 12.-Bathtub model estimated and measured ratios of (Total N – 150)/Total P (●=measured, O=estimated with the Bathtub model using low flow period of September 2001; error bars represent ± 1SE of the mean).

between the average chlorophyll *a* concentration measurements taken at MHL-UpperLake, MHL-MiddleLake1, and the two sampling locations in WR. However, the chlorophyll *a* concentrations predicted by the Bathtub model for MHL-MiddleLake2 and Near Dam in MHL were approximately double the observed value (Fig. 10). Lower chlorophyll *a* concentrations measured in these sampling locations may be related to the dynamic nature of the highly flushed impoundment system and the limits of our calibration data.

Effect of varying total phosphorus concentrations and stream inflows on eutrophication

James *et al.* (2002) studied the effects of phosphorus on eutrophication of Half Moon Lake in Wisconsin. They used the Bathtub model to estimate the effects of reducing total phosphorus load on the reduction of algae concentrations in the lake and developed a management plan for phosphorus control. For the purpose of management evaluations, hypothetical scenarios were simulated with the Bathtub model.

The effect of varying the total phosphorus concentration (from 50% lower to 50% higher than the calibrated value) on the chlorophyll *a* concentrations was investigated for MHL and WR with the Bathtub model (Fig. 11). When total phosphorus concentration was increased by 50%, there was a 40% average increase in the concentration of chlorophyll *a*. When the total phosphorus concentration was decreased by 50%, there was a 50% average decrease in the concentration of chlorophyll *a*. The impacts of phosphorus loading on chlorophyll *a* concentration within each segment of the lakes is slightly different.

The Bathtub model simulation results indicated that by increasing the stream flows from low flow (the study period) to average flow levels of 2001 and maintaining unchanged total phosphorus and chlorophyll *a* concentrations in the three inflowing streams, the total phosphorus and chlorophyll *a* concentrations averaged over MHL and WR would increase by 47% (reaching 35.1 µg/L) and 29% (reaching 11.7 µg/L), respectively (Fig. 9 and 10).

Samples collected at the points where Fenton, Mount Hope and Natchaug rivers entered the MHL were analyzed for selected nutrients and chlorophyll *a* during the September 2001 low flow and the September 2002 storm flow conditions. The measured mean concentrations of total phosphorus, total nitrogen, organic nitrogen, and chlorophyll *a* with ISCO® samplers were compared with the mean values measured during the low flow period of September 2001 (Table 3). The ratios of storm-flow/low-flow concentration of total phosphorus in Fenton, Mount Hope, and Natchaug rivers were 1.0, 0.4, and 0.4, respectively. The corresponding ratios for chlorophyll *a* concentrations were 1.5, 0.5, and 0.3, respectively. These data indicate that the concentration of total phosphorus in the Fenton River does not change with the storm event, whereas the concentration of chlorophyll *a* increases by 50%. It should be noted that Mirror Lake, located on the western highlands of the Fenton River watershed, is a seasonal habitat for Canada geese and migrating ducks. During storm events, this pond flushes to the lower section of the Fenton River with a large load of nutrients and (apparently) algae.

During storm events, it is common for chlorophyll *a* concentrations to decrease, and because the opposite is observed in the Fenton River, more data are needed to reach reliable conclusions about this tributary. Because only one storm event was sampled, statistical inferences could not be drawn.

We observed a sharp increase in the total phosphorus concentration in Fenton and Mount Hope rivers during the early hours of the rainstorm. However, no trend in the total P concentrations measured in the Natchaug River was indicated. In the Fenton River, chlorophyll *a* showed an increase during the early hours of the storm, but no specific trend was observed for chlorophyll *a* concentrations in the Mount Hope and Natchaug rivers. The total nitrogen measurements during the storm event did not indicate any pattern in Fenton, Mount Hope or Natchaug rivers.

Note that mean concentrations for total P, total N, and chlorophyll *a* were used in the data analysis and as input to the Bathtub model. This averaging may have obscured any increasing concentration trends occurred in the three streams during the early hours of the storm (Fig. 13, 14 and 15).

Limiting nutrient index

The overall value for the Bathtub nutrient-limitation index for all sampling locations was about 10, which suggests that either nitrogen or phosphorus might limit eutrophication of the MHL-WR system, with the system (or parts of it) existing in a fragile threshold equilibrium. This also suggests that more detailed study into nutrient limitation may be warranted. A plot for this index was generated with the Bathtub model (Fig. 12), and the measured ratios showed that in two sampling locations (MHL-UpperLake and MHL-MiddleLake1) the index was about 15 (potential P limitation). In the other four sampling locations the ratio ranged between 4 and 12 (potential N limitation).

Summary and conclusions

This study showed that the Bathtub model is capable of estimating total nitrogen, total phosphorus and chlorophyll *a* concentrations of water impoundments with short hydraulic residence times with levels of accuracy that could be meaningful for management evaluations. Results indicated average prediction errors of 2% and 9% for total nitrogen and total phosphorus concentrations, respectively (Fig. 7 and 9). The predictions of total nitrogen results were more accurate in MHL than in WR. The predictions of total phosphorus were equally accurate at all sampling locations, while the predictions of chlorophyll *a* concentration were more accurate at the first two sampling locations in MHL (Fig. 10). The average prediction error for chlorophyll *a* concentration was 54%. The Bathtub model was not suitable for estimation of organic nitrogen because estimation of organic nitrogen in this model was not constrained by, or related to, the observed nitrogen concentration. It is possible to obtain predicted values of organic nitrogen that are substantially higher than the measured values.

Lake sediments may act as either source or sink of organic nitrogen. Therefore, for future studies of the MHL and WR system, more frequent sampling that includes sediments is recommended to provide better insight into the organic nitrogen cycle in the reservoir system. The empirical relationship in the Bathtub model between organic nitrogen and chlorophyll *a* should be investigated further for its suitability to reservoirs with high flushing rates. Comparison with other

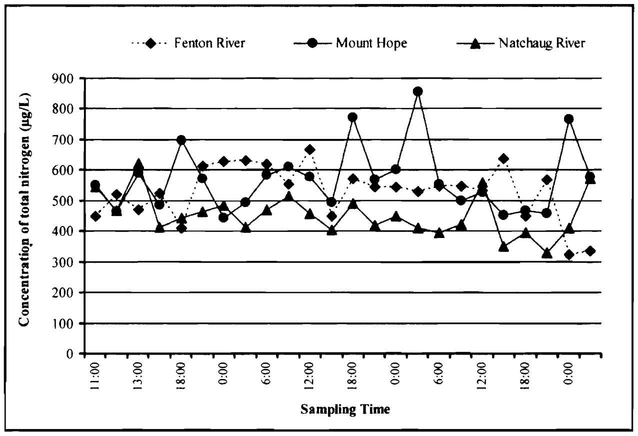

Figure 13.-Total nitrogen concentration variation during the storm event. Samples were taken at the discharge area of the streams to MHL.

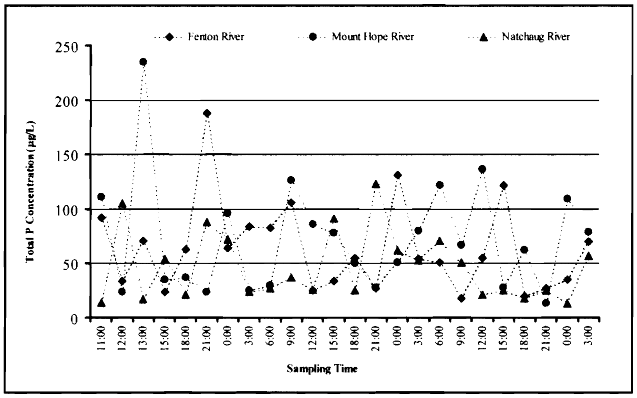

Figure 14.-Total phosphorus concentration variation during the storm event. Samples were taken at the discharge area of the streams to MHL.

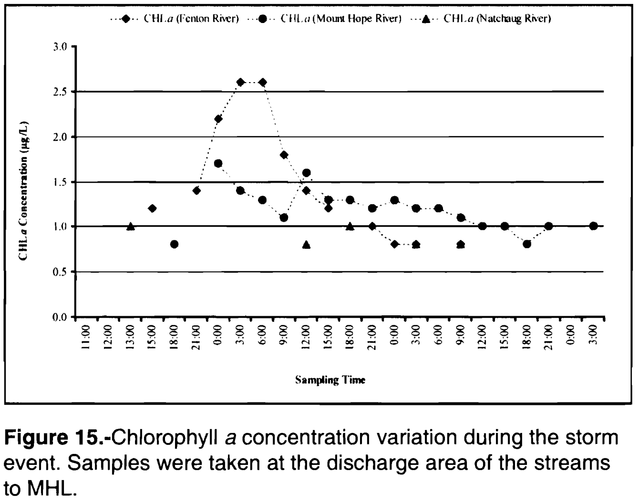

Figure 15.-Chlorophyll *a* concentration variation during the storm event. Samples were taken at the discharge area of the streams to MHL.

models, including transient water quality models, to test the effects of steady state assumptions is suggested.

The sampling campaign conducted during a moderate rainstorm did not show the typical rise in nitrogen or phosphorus associated with nonpoint source pollution systems. This phenomenon may be due to the low intensity of the rainstorm and the consumption of rain water and nutrients through evapotranspiration of dense vegetation covering the watershed. The Bathtub simulation results indicated that compared to low flow conditions total phosphorus and chlorophyll *a* concentrations at average flow could experience a 47% and 29% concentration increase, respectively (Figs. 9 and 10). To validate this hypothesis, more frequent sampling (especially in the three streams discharging into MHL) is needed.

The results of this study indicated that even with limited field data, the Bathtub model can be calibrated and act as an effective tool for assessment of most water quality parameters in the MHL and WR reservoir system.

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References

Burden, R.L., J.D. Faires and A.C. Reynolds. 1981. Numerical Analysis, PWS Publishers, Boston, Mass., 598 p.

CTDEP. 2005. General Statutes of Connecticut, Section 22a-417 (formerly Sec.25-26a). Discharge of sewage into tributaries of water supply impoundments or Salmon River (AKA CGS 22a-426 Standards of Water Quality). Connecticut Department of Environmental Protection. Hartford, Conn., USA.

CTDEP. 2002. Water Quality Standards. Connecticut Department of Environmental Protection. Hartford, Conn., USA.

Dodds, W.K., J.R. Jones and E.B. Welch. 1998. Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Res. 32:1455-1462.

Hoag, G.E. 2003. Monitoring and Analysis of the Willimantic Reservoir and the Mansfield Hollow Lake Watershed. Report submitted to the Willimantic Water Commission, The Environmental Research Institute, University of Connecticut.

James, W.F., J.W. Barko, H.L. Eakin and P.W. Sorge. 2002. Phosphorus budget and management strategies for an urban Wisconsin lake. Lake Reserv. Manage. 18:149-163.

Nadim, F., M.M. Trahiotis, S. Stapcinskaite, C. Perkins, R.J. Carley, G.E. Hoag and X. Yang. 2001. Estimation of wet, dry and bulk deposition of atmospheric nitrogen in Connecticut. J. Environ. Monitor. 3:671-680.

Nadim, F., S. Stapcinskaite, M.M. Trahiotis, C. Perkins, R.J. Carley, S. Liu and X. Yang. 2003. The effect of precipitation amount and atmospheric concentrations on wet deposition fluxes of oxidized and reduced nitrogen species in Connecticut. Water Air Soil Pollut. 143:315-335.

Nadim, F., G.E. Hoag, F.L. Ogden, G.S. Warner and A.C. Bagtzoglou. 2007. Water quality characteristics of two reservoir lakes in eastern Connecticut. Lakes & Reservoirs: Research and Management (unpublished data).

NOAA. 2005. NCDC/Climate at a Glance/Annual Precipitation in Connecticut. National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/oa/climate/research/cag3/NA.html. Accessed March 21, 2005.

PDEP. 2003a. Total Maximum Daily Load (TMDL), Pinchot Lake (Beaver Creek Watershed), York County, Penn. South-central Regional Office Water Management Program. Pennsylvania Department of Environmental Protection. State Water Plan 07E.

PDEP. 2003b. Total Maximum Daily Load (TMDL), Dutch Fork Lake, Washington County, Penn., Pennsylvania Department of Environmental Protection. State Water Plan 20E.

Smeltzer, E. and S. Quinn. 1996. A phosphorus budget, model, and load reduction strategy for Lake Champlain. Lake Reserv. Manage. 12:381-393.

Soballe, D.M. and B.L. Kimmel. 1987. A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes, and impoundments. Ecology 68:1943-1954.

Soballe, D.M. and S.T. Threlkeld 1985. Advection, phytoplankton biomass, and nutrient transformation in a rapidly flushed impoundment. Arch. Hydrobiol. 105:187-203.

Stednick, J. 2000. Phosphorus in Colorado streams and reservoirs, Colorado State University, Dep. of Earth Resources, http://colostate.edu/Depts/SoilsCrop/extension/Newsletters/2000/phosphorus/stream. Accessed October 15, 2005.

USGS. 2005a. Daily stream flow for Connecticut USGS-01121000 Mount Hope River near Warrenville Road, Conn. United States Geological Survey. http://waterdata.usgs.gov/ct/nwis/uv?01121000 Accessed October 15, 2005.

USGS. 2005b. Daily Stream Flow for Connecticut USGS-01122000 Natchaug River at Willimantic, Conn. United States Geological Survey. http://waterdata.usgs.gov/ct/nwis/uv?01122000. Accessed October 15, 2005.

USACE. 2000. Priority pollutant scan, Mansfield Hollow Lake. New England District, Concord, Mass., U.S. Army Corps of Engineers, Report No. OMB-0704-0188.

Walker, W.W. 1999. Simplified procedures for eutrophication assessment and prediction: User Manual Instruction Report W-96-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Walker, W.W. 1987. Environmental and operational water quality studies: empirical methods for predicting eutrophication in impoundments. Report 4: Application Manual. Technical Report E-81-9. Prepared for U.S. Army Corps of Engineers. Waterways Experiment Station, Vicksburg, Miss.

Walker, W.W. 1985. Environmental and operational water quality studies: empirical methods for predicting eutrophication in impoundments. Report 3: Application Manual. Technical Report E-81-9. Prepared for U.S. Army Corps of Engineers. Waterways Experiment Station, Vicksburg, Miss.

Wang, S.H., D.G. Huggins, L. Frees, C.G. Volkman, N.C. Lim, D.S. Baker, V. Smith and F. Denoyelles. 2005. An integrated modeling approach to total watershed management: water quality and watershed assessment of Cheney Reservoir, Kansas. Water Air Soil Pollut. 164:1-19.

Warner, G.S., F.L. Ogden, A.C. Bagtzoglou and P. Parasiewicz. 2005. Long-term analysis of the University of Connecticut's Fenton River water supply wells on the habitat of the Fenton River. University of Connecticut, Draft Final Project Report, 183 p.

Wetzel, R.G. 2001. Limnology. 3rd Edition. Academic Press, 1006 p.