Water Quality Model Evaluations For Scenarios Of Loading Reductions And Diversion Of Domestic Waste Effluent Around Onondaga Lake[1]

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ABSTRACT

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Management models for total phosphorus (TP), various nitrogen (N) species, and dissolved oxygen (DO), for polluted culturally eutrophic Onondaga Lake are developed from models presented and tested earlier in this issue (Doerr et al. 1996a, Canale et al. 1996, Gelda and Auer 1996). The management models are applied to test a wide range of remediation alternatives, corresponding to a wide range of reductions in pollutant loading. The analysis focuses primarily on the effluent (3.5 m^3/s(80 MGD)) received from an adjoining domestic wastewater plant (METRO), though a reasonable upper bound of reductions in tributary TP load also is considered. The decreases in lake TP and total ammonia (T-NH_3) concentrations that could be achieved by partial diversion of METRO, increased treatment at METRO, and reductions in tributary loading, would not be adequate to meet the established in-lake TP goal of 20 µg/L (as a summer average in the upper waters), the T-NH_3 standard for the lake (0.77 mgN/L for the upper waters in summer), nor the DO standard for the lake's upper waters (daily average ≥ 5 mg/L). Diversion of the entire METRO discharge around the lake is found to be necessary to meet the T-NH_3 standard, to approach or meet the TP concentration goal, and to avoid violation of the DO standard in the upper waters during fall. Reductions in the prevailing tributary TP load, of as much as 30%, may be necessary to reach the TP goal.

Key Words: management models, model, predictions, goals, standards, diversion, bypass, phosphorus, ammonia, oxygen.

Water quality modeling serves two important, and at times disparate, purposes: (1) to support effective management of water resources by providing reliable predictive tools, and (2) to support basic research, by providing quantitative frameworks for the synthesis of scientific data. These management and research purposes are mutually consistent on a long-term basis, as related research advancements have lead to improved capabilities and credibility of mechanistic management models (Chapra and Reckhow 1983, Thomann and Mueller 1987).

Preceding manuscripts in this issue have documented the development and successful testing of water quality models for total phosphorus (TP; Doerr et al. 1996a), total ammonia (T-NH_3) and other nitrogen (N) species (Canale et al. 1996), and dissolved oxygen (DO; Gelda and Auer 1996), for Onondaga Lake. These models are intended to meet both the management and research purposes stated above. The models will serve to identify and test hypotheses for ongoing research on the lake (e.g., Effler 1996) and guide related programs. The models can be expected to evolve and to be integrated into a single holistic model as research on the lake continues.

The TP, N, and DO models for Onondaga Lake are applied here to investigate the feasibility of reaching related water quality standards and goals for this polluted (Effler 1996, Effler et al. 1996a) lake, and to evaluate selected remediation alternatives. Management alternatives focus primarily on the Metropolitan Syracuse Wastewater Treatment Plant (METRO), the major external source of phosphorus (P), T-NH_3, and oxygen demanding substances, to the lake (Effler 1996, Effler et al. 1996a). Options addressed here include a wide range of reductions of waste loading from the facility via the existing surface discharge to the lake, extending to full diversion around the lake, and a fractional reduction in tributary TP loading. Additionally, as part of the analysis we: (1) review related water quality goals and standards for the

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lake, (2) develop appropriate sets of inputs to support management runs with the models, (3) describe linkages between the models for management applications, and (4) describe limitations in the analysis. An analysis of the impact of a deep-water discharge alternative for METRO's effluent is presented subsequently in this issue by Doerr et al. (1996b).

Onondaga Lake, METRO, and Standards

Onondaga Lake is a medium size (surface area of 12.0 km^2, and mean depth of 12 m), rapidly flushed (average of 3.9 flushes/y; Effler and Hennigan 1996), dimictic, urban lake that adjoins Syracuse, NY. The history of the development of this area, the lake's setting, morphometry, hydrology, and selected features of its degraded state, have been reviewed by Effler and Hennigan (1996). The effluent from METRO makes extraordinary contributions to hydrologic and critical water quality constituent budgets for the lake. This discharge represents nearly 20% of the total inflow to the lake, and approximately 60 and 90% of the total external loads of TP and T-NH_3, respectively (Effler et al. 1996a). The outflow of Onondaga Lake enters the Seneca River approximately 10 km from the METRO facility.

The extremely high loading rates of TP (~8 $g/m^2/y$) and (~200 $g/m^2/y$; about 90 $g/m^2/y$ as T-NH_3), associated largely with the METRO contribution, severly impact the lake (e.g., Effler 1996, Effler et al. 1996a). Recurring degradations in water quality associated with the cultural eutorphication of the lake include excessively high concentrations of phytoplankton biomass, poor clarity, rapid loss of oxygen from the hypolimnion, and lake-wide depletion of oxygen during the fall mixing period (Effler et al. 1996a). The New York State (NYSDEC 1993) "guidance value" (open to some regulatory dicretion) for TP concentration (summer epilimnetic average, TP_e) of 20 μg/L is exceeded by a factor of three or more. The clarity standard (4 ft, or ~1.2 m) for opening a bathing beach in New York State is violated, as are the DO standards for surface waters in the state (4 mg/L daily minimum, and 5 mg/L daily average).

The chronic non-salmonid standard for free ammonia (NH_3) to protect against the toxic effects of this species is violated routinely, and by a wide margin, in the upper waters of the lake in summer (Effler et al. 1990, 1996a). Violation of the acute non-salmonid standard for NH_3 has been documented in some years (e.g., Effler et al. 1990, 1996a). These violations are attributed largely to excessively high concentrations of T-NH_3 in the lake (Effler et al. 1990, 1996a). The fraction of T-NH_3 that exists as NH_3 and the standards for NH_3 (USEPA 1985) are primarily a function of pH, and secondarily temperature. In 1994 the state regulatory agency (NYSDEC) established in-lake standards for T-NH_3 (to protect against violations of the NH_3 standard) for the upper waters of the lake. The "summertime" and "wintertime" values are 0.77 and 1.07 mgN/L, respectively. The boundary dates will probably be about June 1 and October 1, though the evolution of a more temporally detailed distribution for the standard is a distinct possibility.

Onondaga Lake Management Models

General Description, Specification of Inputs

Personal computer-based management models to support *a priori* (e.g., futuristic) predictions of lake water quality have been developed from the tested TP, N, and DO models. All three models have the same physical framework, two vertical completely mixed layers, the upper mixed layer (UML) and the lower mixed layer (LML), with a demarcation depth of 8.5 m. The programs retain the basic model structures, most of the kinetic coefficient values, and certain forcing conditions developed for the models. However, other forcing conditions and state variables of management interest become user-defined. Conditions incorporated in the management models are of two types, "hard-wired" or "built-in", which are not subject to change by the user, and "default", which the user can override (Table 1).

Physical characteristics not subject to management action are built-in to the management models (Table 1). Several of these have been handled identically for the three models because of the unifying manner in which each treats the stratification/ vertical mixing regime. Realistic variations in the vertical mixing coefficient (v_t) have a relatively minor effect on the concentrations of important constituents in the UML during the summer (e.g., Doerr et al. 1996a). Wind speed is subject to substantial natural year-to-year variations in this region (Effler et al. 1986, Owens and Effler 1989), which in turn can have significant impact on DO concentrations at fall turnover (Gelda and Auer 1996). Similarly, natural variations in tributary flow are important in establishing the late spring/early summer

Table 1.–Conditions specified in lake management models; TP, N species, and DO.

	Description	TP	N species	DO
a. Built - In Parameters				
1. Physical				
(a). layer temperature	interpolated temperatures	1990	1989	1989
(b). vertical mixing, v_t		1990	1989	1989
(c). settling, velocity		214 m/yr	214 m/yr	—
PP:TP		polynomial 1990	—	—
(d). wind speed	Hancock Airport, daily average	—	—	average of 1989 and 1990; U_{10}
2. Loadings, Tributary				
(a). flows and loads	daily (Effler and Whitehead 1995)	1987 and 1990	1976, 1986, 1987	1986
3. Stoichiometry				
(a). fraction T-NH_3 as NH_3		—	1989	—
(b). p-PON/CHL		—	5.2	—
(c). DO model		—	—	a_{CP}=42.7, a_{OC}=2.7
4. Standards / Guideline		20 µg/L	summertime = 0.77 mgN/L wintertime = 1.07 mgN/L	—
5. Kinetics				
(a). sediment release		*$R_{sed,8}$=13.3mg/m²/d	*$S_{r,8}$ = 70 mg/m²/d	—
(b). other		— — — —	$k_{decomp,20}$ = 0.1/d $k_{hyd,20}$ = 0.005m/d $k_{fn,20}$ = 0.135 m/d $k_{fd,20}$ = 0.4 m/d $K_{L,NH3}$ = 0.17 m/d	$K_{L,DO}$=f(U_{10}) K_{CBOD}=0.28/d $K_{s,DO}$=3.5 mg/L f=0.72
(c). net phyto. growth	$G_{NET,89}$	—		—
b. Default				
1. METRO				
(a). flow	monthly avg. 1988-1990	X	X	X
(b). load		1990 annual average	polynomial 1988-1990	1990 monthly average
2. tributary flow and load		1990	1986	1986
3. fraction reduction on trib. load		0-1, 0=default	—	—
4. trophic state		—	$TP_{S,89}$ = 75 µgP/L	file from N model
5. DON/TON METRO		—	0.62	—
6. SOD		—	—	*1.68 g/m²/d

symbols: PP - particulate P conc.
U_{10} - wind speed at height of 10 m
p-PON - phytoplankton particulate organic N conc.
CHL - chlorophyll conc
a_{cp} - phyto. carbon/CHL
a_{oc} - oxygen equivalent of phyto. carbon
$R_{sed,8}$ - sediment release rate of P, 8°C
$S_{r,8}$ - sediment release rate of T-NH_3, 8°C
$k_{decomp,20}$ - decomposition rate, of 20°C
$k_{hyd,20}$ - ammoniafication rate, 20°C
$k_{fn,20}$ - nitrification rate, 20°C
$k_{fd,20}$ - denitrification rate, 20°C
K_{LNH3} - surface transfer coeff. for NH_3
$K_{L,DO}$ - surface transfer coeff. for DO
K_{CBOD} - CBOD oxidation rate
$K_{S,DO}$ - half-saturation constant
f - fraction SOD from CH_4, H_2S, Fe^{2+}

* sediment exchange rate values for full diversion scenarios
$R_{sed,8}$ = 5 mg/m²/d SOD = 0.7 g/m²/d
$S_{r,8}$ = 10 mg/m²/d

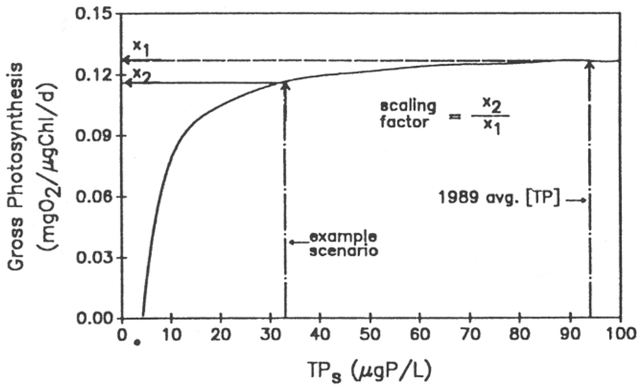

Figure 1.–Gross photosynthesis per unit chlorophyll as a function of summer average TP concentration, developed across trophic state gradient of Green Bay Lake Michigan by Auer et al. (1986). Example of use to develop "scaling factor" to adjust G_{NET} in the N model and SOD in DO model.

concentration of T-NH_3 in the lake's upper waters (Effler et al. 1996a), and thereby the margin of violation of related standards (Canale et al. 1996). Thus the unavoidable specification of environmental forcing conditions, such as wind speed and tributary flow, necessary to support *a priori* predictions with the management models, inherently introduces a degree of uncertainty for futuristic (including long-term) predictions.

Trophic State, Model Linkages, NO_3^- Limitation

Changes in the phytoplankton sink for T-NH_3 (Canale et al. 1996) and source for DO (Gelda and Auer 1996) that would result from changes in trophic state need to be accommodated to support futuristic projections for scenarios that include major reductions in P loading. The Monod-type relationship between the summer average epilimnetic TP concentration and gross photosynthesis developed by Auer et al. (1986), for the trophic state gradient that prevails across Green Bay, Lake Michigan (Fig. 1), has been adopted. The Monod character of the relationship is quite important. Summer average epilimnetic TP concentrations (TP_e) >40 μg/L are essentially saturating (Fig. 1). Thus, little reduction in growth is achieved until TP_e decreases below this saturating threshold. The 1989 distributions for net phytoplankton growth ($G_{NET,89}$; see Table 1) developed by Canale et al. (1996) have been adopted in the N management model as generally representative of the recurring "shape" (seasonality) for the lake. The magnitude of G_{NET} for a specified scenario ($G_{NET,S}$) is "scaled down" for reduced TP concentrations according to the relationship of Auer et al. (1986; Fig. 1).

The Onondaga Lake TP, N and DO management models are linked to the extent that output of one serves as input to the other, in the sequence, TP → N → DO. This is the appropriate sequence of operation of the three models for a selected management scenario. The TP model predicts the TP_e of the UML. This becomes one of the inputs to the N model which generates the distribution of $G_{NET,S}$, and predicts distributions of concentrations of chlorophyll and T-NH_3 (Canale et al. 1996); these become inputs to the DO model.

Nitrate (NO_3^-) was assumed not to be assimilated by phytoplankton in the testing of the N model (Canale et al. 1996). This was justified because of the prevailing high concentrations of T-NH_3 in the lake, the form of N (as NH_4^+) preferred (versus NO_3^-) for growth for energetic reasons (Wetzel 1983). The kinetics of phytoplankton uptake of N have been modified for the UML in the N management model to accommodate scenarios in which the concentration of T-NH_3 would decrease to levels which favor NO_3^- uptake as an alternate source of N. The switch from T-NH_3 to NO_3^- uptake is fixed at a T-NH_3 concentration of 50 μg/L. The respective mass balance equations for T-NH_3 and NO_x (sum of NO_3^- plus NO_2^-) are modified according to the expressions presented in Canale et al. (1993).

Loads and Flows

Users of the management models are provided an input screen for entering monthly average discharge flow and effluent concentrations from METRO; TP concentrations for the TP model, T-NH_3, NO_x, and total Kjeldahl N for the N model, and BOD (5-day) for the DO model. Organic N (TON) in the effluent is partitioned into particulate organic N and dissolved organic N (DON) concentrations in the N management model, either according to the ratio DON:TON = 0.62 (Table 1), the average reported for 1989 and 1990 (Onondaga County 1990, 1991), or by a user specified ratio. Predictions of T-NH_3 are generally insensitive to realistic variations in this partitioning. Recall that Gelda and Auer (1996) found that the external load of oxygen demanding substances was low compared to that produced internally, associated with the lake's eutrophic condition. Default conditions of flow and constituent concentrations have been specified for the METRO effluent (Table 1).

Two tributary flow and TP loading regimes are provided in the TP model (see "built-in parameters" of Table 1 for options) to reflect the influence of natural variability in runoff on TP concentrations in the lake. The regimes correspond to conditions documented in 1987 and 1990, that represent a wide range in tributary flow and for which particularly detailed tributary TP loading information is available (Doerr et al. 1996a, Effler and Whitehead 1996). The third highest tributary flow over the 1971-1990 (20 yr) interval occurred in 1990; the second lowest over that interval was observed in 1987 (Effler and Whitehead 1996). Tributary loading reduction scenarios are accommodated in the TP model with a fractional reduction multiplier (e.g., 0.1x corresponds to a 10% reduction in tributary loading), that is applied uniformly throughout the 1990 or 1987 loads.

Three flow regimes are represented in the N management model (see "built-in parameters", Table 1) to reflect the important influence of natural variability in runoff on T-NH_3 concentrations (Canale et al. 1996, Effler et al. 1996a). The three runoff options in the management model include: (1) 1986, a year that approaches the median flow for the 1971-1990 period, (2) 1976, the second highest flow year over the 1971-1990 period, and (3) 1987, the second lowest flow year for the 1971-1990 period. The 1987 case, which corresponds essentially to a one in ten years return frequency, is generally consistent with the widely adopted approach for specifying critical flow conditions in waste assimilative capacity studies for streams and rivers (e.g., Thomann and Mueller 1987). The corresponding tributary loads (also see Canale et al. 1996) of the N species for these flow regimes are calculated, with the exception of the Ninemile Creek T-NH_3 and NO_x loads, using temporally uniform concentrations equal to the observed averages. This simplification is supported by observations and the fact that METRO is presently the dominant source of N (particularly T-NH_3) species (Effler and Whitehead 1996, Effler et al. 1996a). The Ninemile Creek T-NH_3 and NO_x loads are calculated according to documented flow-concentration relationships (Effler et al. 1991, Effler and Whitehead 1996).

Predictions of the TP management model for the UML for the lake were quite similar for the specified low and high runoff conditions. This reflects uniformity in the METRO input and the compensating effect of slightly decreasing TP concentration with increasing flow observed for the major tributaries (Effler and Whitehead 1996). The dry year (1987) option is utilized in subsequent projections for selected management scenarios to maintain consistency with the critical dependence of lake T-NH_3 concentration on tributary flows, demonstrated below.

Simulations of T-NH_3 concentration in the UML generated with the N management model, using default inputs, are presented for the three tributary flow options (Fig. 2). The critical role tributary flow plays in diluting the METRO loading (highest T-NH_3 concentrations for the lowest tributary flows, 1987 conditions), demonstrated earlier with empirical (Effler et al. 1996a)

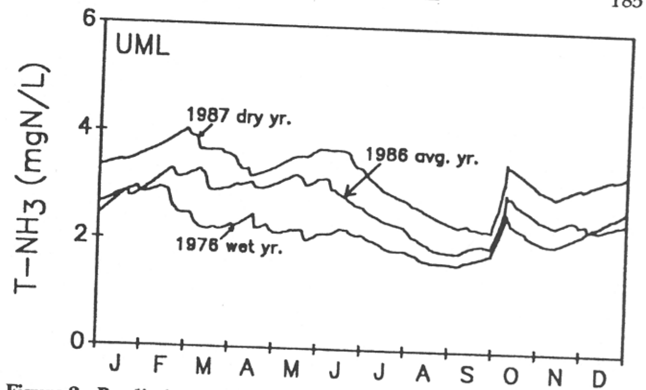

Figure 2.–Predictions of T-NH_3 for the upper mixed layer (UML) of Onondaga Lake from N management model, for three tributary flow cases.

and sensitivity (Canale et al. 1996) analyses, is clearly depicted in these simulations. The "low flow", 1987, case has the greatest value for evaluating management scenarios, as it can be described as a reasonable "critical conditions" case. This low flow case was adopted in the subsequently presented evaluations of management scenarios. Simulations for the "average" flow case fall below those for the "high flow" case in December (Fig. 2) because tributary flow was substantially higher in December in 1986 than in 1976.

All management model predictions are for the fourth year of consecutive simulations for the specified conditions. These are representative of steady-state conditions for this system (i.e., predictions do not change for longer simulation periods). Initial conditions were those simulated for the specified test year as part of model testing (Canale et al. 1996, Doerr et al. 1996a, Gelda and Auer 1996).

Sediment Feedback

Prevailing sediment feedback in Onondaga Lake has been quantified through laboratory experiments conducted on intact core samples (Gelda et al. 1995, Penn et al. 1993) and model calibration (Canale et al. 1996). These fluxes implicitly accommodate prevailing conditions in the overlying water column (e.g., phytoplankton growth, deposition and decomposition). The existing Onondaga Lake water quality models (Canale et al. 1996, Doerr et al. 1996a, Gelda and Auer 1996) do not simulate the changes in sediment feedback that would occur in response to major improvements in overlying water quality. Modeling of sediment feedback is an active research area (e.g., Chapra and Canale 1991, DiToro et al. 1990, Snodgrass 1987), and related research is on-going for Onondaga Lake (Penn 1994, Stromquist 1995).

Decreases in the sediment release rates of P ($R_{sed,8}$) and T-NH_3 ($S_{r,8}$), and sediment oxygen demand (SOD;

Table 1) would occur if a reduction in the external TP loading rate was adequate to shift the lake from its present eutrophic state to mesotrophy (e.g., Gelda and Auer 1996, Penn 1994). Recently reported estimates of steady-state values of $R_{sed,8}$ (Penn 1994) and SOD (Gelda and Auer 1996) for a mesotrophic Onondaga Lake have been adopted for management scenarios that include complete diversion of the METRO effluent around the lake (Table 1; see subsequent simulations of TP_e). These values are conservative. For example, the value of $R_{sed,8}$ does not reflect the benefit of reductions in tributary loading of P (Penn 1994). The SOD value (0.7 g/m²/d; Table 1) is the maximum of the range estimated by Gelda and Auer (1996) for mesotrophy. The value of $S_{r,8}$ was reduced for full diversion scenarios, based on Gelda and Auer's (1996) estimated SOD value, according to the relationship of DiToro et al. (1990). These rates were kept at the default (prevailing) values for scenarios that did not include complete diversion of METRO because the TP loading reductions would not be great enough to achieve mesotrophic conditions. No effort is made here to simulate conditions during the transition period, as the lake comes into equilibrium with the underlying sediments (e.g., DiToro et al. 1990, Lorenzen et al. 1976). Penn (1994) has estimated the period to reach steady-state for sediment phosphorus release in Onondaga Lake to be about 30 y.

Management Alternatives

Leading management alternatives under consideration to remediate the impacts of METRO on Onondaga Lake have been selected to illustrate the

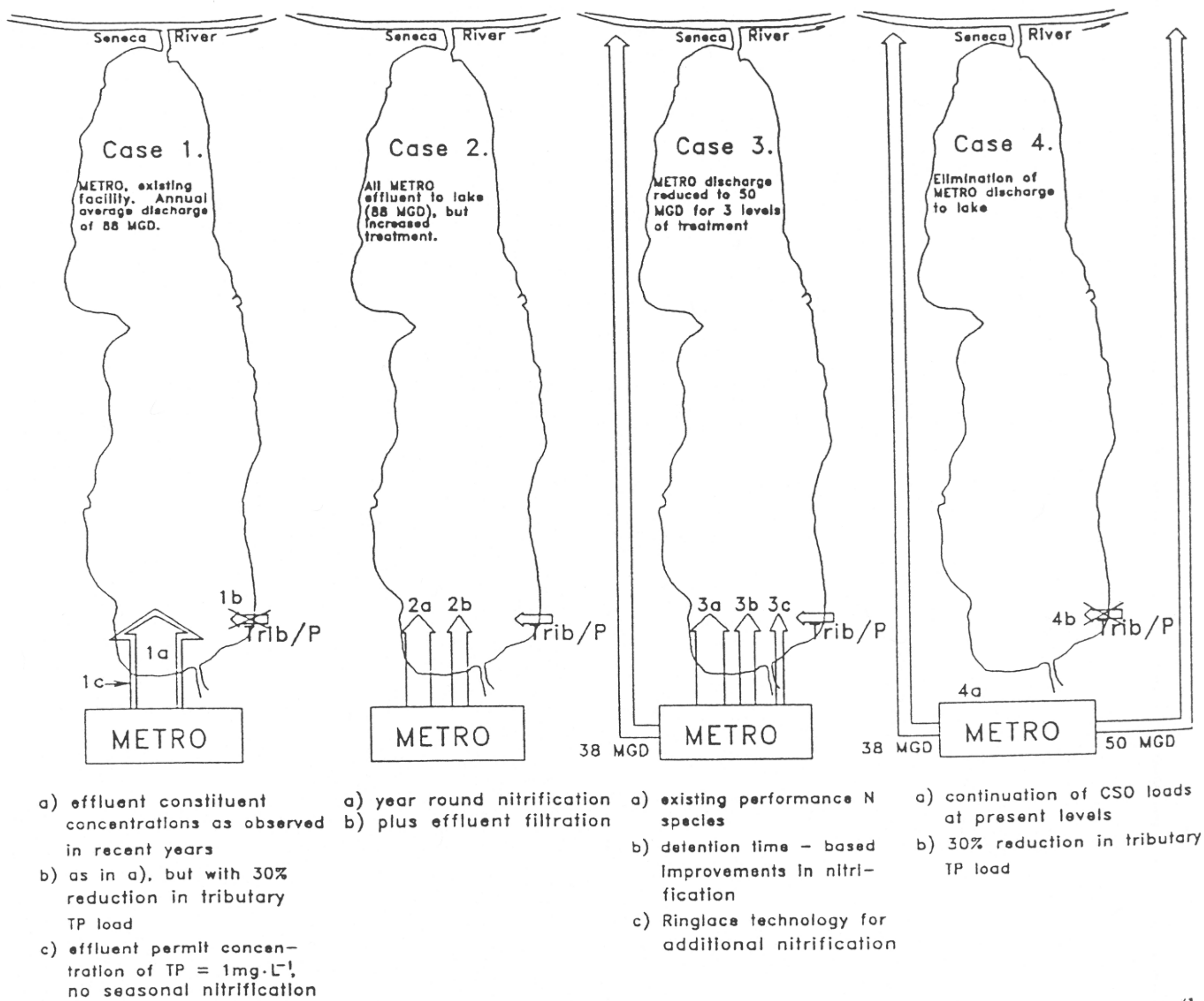

Figure 3.–Selected management alternatives for METRO and tributary TP loading to be evaluated with lake management models, as cases (1-4) and sub-cases.

utility of the management models in supporting related deliberations. Reductions in tributary loading of TP associated with treatment of irregular inputs of dilute raw sewage received during combined sewer overflow (CSO) events (Effler and Hennigan 1996), in combination with appropriate landuse practices, are also evaluated. There are three salient features of the alternatives considered. One is the level of treatment at METRO; the second is the inclusion of reductions in tributary loading; and third is the location of the METRO discharge. A wide range of P and T-NH_3 treatment at METRO is considered. METRO discharge options include diversion around the lake, the surface waters of the lake, and a deep-water position. The analyses presented here are limited to the first two alternatives. The deep-water discharge option requires modifications in the transport framework of the water quality models. These modifications and an evaluation of the deep-water discharge option, are described subsequently in this issue (Doerr et al. 1996b).

The alternatives are lumped into four main cases, numbered 1 through 4; sub-cases within each case are identified alphabetically, e.g., sub-cases 3a, 3b, and 3c (Fig. 3). Loading data developed to support these evaluations are from a variety of sources, including historic performance data for METRO (Stearns & Wheler 1993b) and from other facilities presently operating processes incorporated here as components of the selected scenarios. The fine features of these alternatives may change with continued input from design engineers and regulators. However, they are generally representative and more than adequate to demonstrate the utility of these management tools and identify the most promising alternative(s).

Seasonal distributions, as monthly averages, of the METRO flow, and TP and N species concentrations in the effluent of the facility have been specified for the various cases (Fig. 4). A consistent set of BOD concentrations (e.g., Stearns & Wheler 1993a, b) were used to support application of the DO management model. The BOD distributions are not shown because predictions are relatively insensitive to this range of concentrations of this relatively minor DO sink. The projected annual average flow developed for METRO (Stearns and Wheler 1992) of 3.85 m^3/s (88 MGD) was adopted for the analysis; this is about 20% higher than the average flow reported for the facility in 1989. The relative seasonality adopted (Fig. 4a) is consistent with historic observations.

Case 1 addresses the continued discharge of the entire effluent flow from the existing facility (Fig. 3). Sub-case 1a assumes performance characteristics for TP, N species, and BOD removal consistent with recent loading conditions (Stearns & Wheler 1993b, very similar to the default inputs of the management models

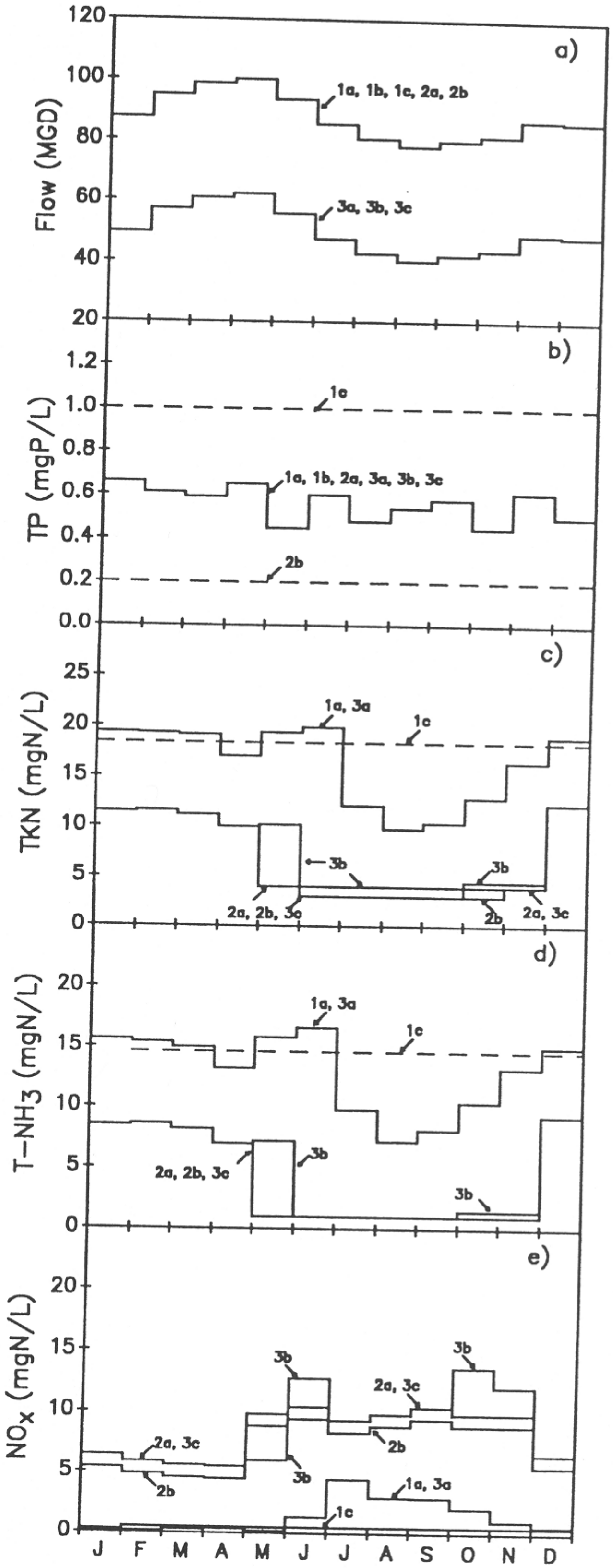

Figure 4.–Seasonal distributions, as monthly averages, of METRO flow and effluent concentrations for cases of Fig. 3: (a) flow, (b) TP concentration, (c) TKN concentration, (d) T-NH_3 concentration, and (e) NO_x concentration.

(Table 1)), which reflect seasonal nitrification and TP removal beyond that required by the existing permit for the facility (effluent TP concentration = 1 mg/L; Fig. 4). Sub-case 1b represents a reasonable upper bound of tributary loading reduction for TP (30%), that reflects effective treatment (75%) of the CSO component (e.g., storage of 1 y storms) as well as an aggressive landuse management program for the non-urban portions of the watershed (20% reduction; see Effler and Whitehead 1996). Sub-case 1c assumes a TP concentration in the effluent of 1 mg/L and no seasonal nitrification (Fig. 4), consistent with the design of the facility and its earlier performance. Comparison of model simulations for sub-cases 1a and 1c depicts the benefits achieved through efforts made to optimize the performance of the existing facility.

Case 2 represents continued discharge of all of METRO's effluent to the lake, but with additional treatment (Fig. 3). Sub-case 2a reflects increased nitrification. The N species concentrations assumed correspond to those observed for a 7.45 m^3/s (170 MGD) operating facility in Baltimore, Maryland, that has nitrification treatment. Note T-NH_3 and TKN concentrations remain higher in the winter months (Fig. 4) because of reduced treatment efficiency at lower temperatures. The TP concentration of the effluent is assumed not to be affected (i.e., same distribution as case 1a) for this scenario. Sub-case 2b corresponds to the addition of effluent filtration to sub-case 2a. The 0.2 mg/L TP concentration of the effluent assumed for this case (Fig. 4) is consistent with the NPDES permit and operating results for the Baltimore facility. The temporal distributions of T-NH_3 and NO_x for sub-case 2b are nearly identical to those for sub-case 2a. Sub-case 2b can fairly be described as representing a high degree of treatment for a large scale facility.

Case 3 represents an alternative that includes diversion of 1.65 m^3/s (38 MGD) of waste water presently received by METRO from a portion of its service area to a treatment plant on the Seneca River (Fig. 3). Accordingly, METRO would discharge 2.2 m^3/s (50 MGD) to the lake, instead of 3.85 m^3/s (88 MGD) (Stearns & Wheler 1993a). The three sub-cases correspond to varying levels of nitrification. The present loading conditions for TP specified by Stearns & Wheler (1993b), used previously in sub-cases 1a and 2a, were applied for case 3 (Fig. 4). Sub-case 3a represents a worst case, it corresponds to the existing seasonality in N species concentrations (Fig. 4, used also for sub-case 1a). Sub-case 3b reflects an increased level of nitrification (Fig. 4) that is consistent with the increased detention time within METRO associated with this partial bypass scenario (Stearns & Wheler 1993a). Sub-case 3c corresponds to the additional nitrification that may be achieved by use of an innovative (e.g., Ringlace) technology (Fig. 4).

Case 4 represents full bypass of the METRO discharge around Onondaga Lake (Fig. 3). This has included a single pipe and two-pipe alternatives to the Seneca River (Onondaga Lake Management Conference 1993), but could also include diversion further downstream (e.g., Lake Ontario). The position of the diversion of course has no effect on the lake, but has implications for the system that receives the diverted flow (Effler 1996). Sub-case 4a corresponds to tributary TP loadings at the prevailing level, accommodated in the default tributary loading conditions. Sub-case 4b corresponds to the 30% reduction in tributary loading specified in sub-case 1b.

Management Model Predictions

Total Phosphorus

The predictions of TP for the UML of Onondaga Lake from the TP management model for the evaluated scenarios (Figs. 3 and 4) are presented as a family of temporal distributions (Fig. 5; corresponding TP_e values (mid-May to mid-September) appear in Table 2). The

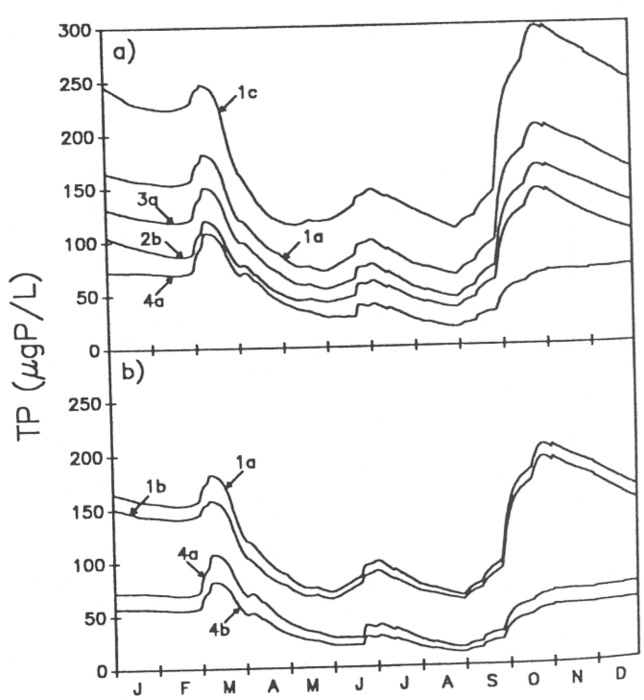

Figure 5.–Predicted seasonal distributions for TP concentration in the upper mixed layer (UML) of Onondaga Lake: (a) sub-cases 1a, 1c, 2b, 3a, and 4a, and (b) sub-cases 1a, 1b, 4a, and 4b.

Table 2.–Predicted summer average (mid-May to mid-September) TP concentrations for the upper mixed layer of Onondaga Lake for selected METRO/Tributary scenarios, bounds of mesotrophy, and NYSDEC guidance value.

METRO/Tributary Scenarios	Case*	$[TP]_e$ (μg/L)**
1. Existing METRO, [TP] in effluent at permit concentration (1 mg/L), 88 MGD	1c	126
2. Existing METRO, at prevailing [TP] in effluent, 88 MGD	1a	79
3. Existing METRO, with 30% reduction in tributary load	1b	73
4. Upgrade METRO to effluent filtration, all effluent to lake surface, 88 MGD	2b	46
5. Reduced METRO discharge to lake surface (50 MGD), at prevailing [TP]	3a	59
6. Complete METRO bypass of lake, tributary load remains	4a	28
7. Complete METRO bypass of lake, with 30% reduction in tributary load	4b	21
Bounds of Mesotrophy		
Vollenweider 1975		10-20
Chapra and Dobson 1981		10-21.7
Vollenweider 1982		9-35
Auer et al. 1986		11.5-37.5
NYSDEC+ (1993) Guidance Value		20

* see Figs. 3 and 4.
** mid-May through mid-September.
+ New York State Department of Environment Conservation.

concentrations of TP in the lake in summer would presently be about 60% greater if METRO operated at its permit limit of 1 mg/L (sub-case 1c), instead of the higher performance, achieved in recent years (sub-case 1a, Table 2). However, little if any benefit with respect to phytoplankton growth in the lake is realized by this reduction because the recent lower concentrations remain nearly saturating (Fig. 1; Connors et al. 1996). A reasonable upper bound to reductions in tributary loading would result in a relatively minor reduction in lake concentration, at the prevailing METRO loading rate (Figure 5b, Table 2), and would not be expected to significantly influence phytoplankton growth.

Substantial numerical reductions in lake TP concentrations would result from either partial bypass (case 3) or upgrading METRO to effluent filtration (sub-case 2b; Figure 5a, Table 2). However, neither option, even in combination with the reduction in tributary loading scenario (not shown), would reduce TP concentrations adequately to significantly reduce phytoplankton growth and achieve mesotrophic conditions. The only option(s) evaluated that would achieve a shift to mesotrophy (i.e., substantial reductions in phytoplankton growth) for Onondaga Lake are those that include full bypass, or diversion, of METRO's effluent around the lake. The predicted TP_e for complete bypass, without reduction in tributary loading (sub-case 4a), is 28 μg/L (Table 2). For the wet year option of the management model (not shown), the predicted TP_e is 31 μg/L. These concentrations are within the mesotrophic range according to certain researchers (Auer et al. 1986, Vollenweider 1982; Table 2).

The fraction of the tributary load subject to management action increases in relative importance with the elimination of the METRO load (sub-case 4b). Numerically this manageable tributary component would represent a larger fraction of the total load. More importantly, within this lower range of concentrations (Fig. 5b, TP_e = 21 μg/L, Table 2) lake primary productivity is more responsive to reductions in TP concentrations (e.g., Fig. 1)). Thus, though tributary reduction efforts would have very little benefit with METRO discharging to the lake, these same efforts would have substantial benefit following the diversion of the METRO discharge around the lake. The New York guidance value of 20 µg/L could be very nearly approached (Table 2), and perhaps attained by the external loading reductions corresponding to sub-case 4b. Note further that the predicted value of TP for this scenario is essentially consistent with the most rigorous boundary of mesotrophy presented in the literature (Table 2).

Predictions of TP_e for sub-case 4b should be considered conservative for two reasons. First, because the value of $R_{sed,8}$ would probably be even lower than predicted by Penn (1994) if substantial reductions in tributary loading were achieved (e.g., sub-case 4b). Second, and probably more important, the fraction of P in the METRO effluent that is dissolved (and thus likely to enter into the P cycle of the UML and be available to support phytoplankton growth) is substantially greater than in the lake's tributaries (Effler et al. 1995).

T-NH$_3$

The predictions of T-NH_3 for the UML of Onondaga Lake for the evaluated scenarios (Figs. 3 and 4) are presented as a family of temporal distributions (Fig. 6). The newly established standard(s) for T-NH_3 in the upper waters of the lake is included for reference. The margin of violation is represented as the ratio of the T-NH_3 concentration [T-NH_3] and the standard. Selected statistics describing the margin of violation for the various scenarios, for the major recreation interval of mid-May to mid-September, are presented (Table 3); these include the maximum value of the ratio [T-NH_3]/standard, and the average over the mid-May to mid-September interval.

Progressive reductions in predicted lake concentrations of T-NH_3 (Fig. 6), and associated margins of violation of the standard (Table 3), track the reductions in METRO effluent concentrations (Fig. 4) and loading for the various scenarios. The seasonal nitrification presently achieved at METRO reduces the margin of violation in late summer, but has no benefit during the critical late spring/early summer period, when the margins of violation are most severe (Fig. 6). Substantial reductions in the margin of violation are predicted for the addition of year-round nitrification at METRO (sub-cases 2a and 2b) and for reductions in METRO's discharge flow combined with increased nitrification (sub-cases 3b and 3c; Fig. 6, Table 3). However, violations remain nearly continuous over the late spring to mid-summer period for all the options except total bypass (Fig. 6). The maximum margins of violation are predicted to be ≥ 1.8 for all options except total bypass.

The total bypass/complete diversion of METRO scenario would eliminate violations of the T-NH_3 standard(s) for the upper waters of the lake (see sub-case 4b of Fig. 7). The model was also used to determine the T-NH_3 concentrations in the METRO effluent that would be necessary to meet the standard for an in-lake (100%) discharge, for the critical tributary flow conditions of 1987. Effluent T-NH_3 concentrations of 2 mgN/L, during the colder late fall through winter interval, and 1 mgN/L, during the spring through early fall period, would be required to (just barely) avoid violation of the in-lake T-NH_3 standard. Achieving this level of nitrification during the cold months is problematic. For example, note the much higher concentrations that prevail at the existing Baltimore facility (Fig. 4d). We are not aware of a large scale operating domestic wastewater facility that routinely achieves this level of nitrification in the colder climates of the United States.

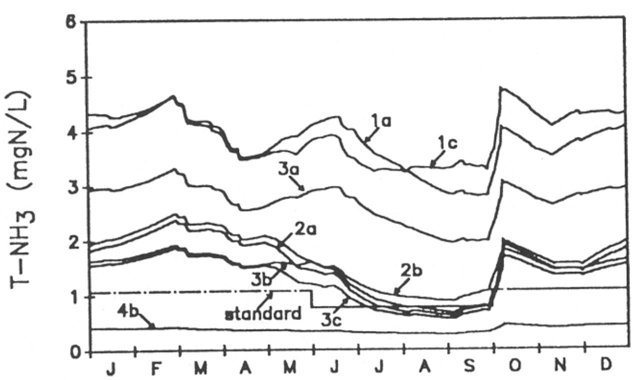

Figure 6.–Predicted seasonal distributions for T-NH_3 concentrations in the upper mixed layer (UML) of Onondaga Lake, with non-salmonid standard for reference, for sub-cases 1a, 1c, 2a, 2b, 3a, 3b, 3c, and 4b.

DO

Simulations of DO are presented for two scenarios (Fig. 7) that are generally representative of in-lake discharge and diversion options for METRO. The predicted in-lake discharge scenario corresponds to prevailing conditions (e.g., Effler 1996, Effler et al. 1986, Gelda and Auer 1996) associated with the eutrophic state of the lake. The improvements indicated for the diversion case reflect the benefits of achieving mesotrophy for the lake (e.g., Gelda and Auer 1996), that would be attained when the sediments come into equilibrium with the lake's water column (i.e., when steady-state conditions are reached).

There are several salient features of the predicted improvement in oxygen resources that would result

Table 3.–Predicted status of UML of Onondaga Lake with respect to non-salmonid T-NH_3 standard for selected METRO scenarios.*

METRO/Tributary Scenarios	Case	$\left[\frac{[T\text{-}NH_3]}{stand.+}\right]^*_{max}$	$\left[\frac{[T\text{-}NH3]}{stand.}\right]^{**}_{avg}$
1. Existing METRO, N-species in effluent consistent with no seasonal nitrification, 88 MGD	1c	5.1	4.5
2. Existing METRO, at prevailing N species in effluent, 88 MGD	1a	5.5	4.6
3. Upgrade METRO, year-round nitrification, 88 MGD	2a	2.2	1.3
4. Reduce METRO discharge to lake, prevailing N species in effluent, 50 MGD	3a	3.9	3.2
5. Reduce METRO discharge to lake, detention - time based improvements in nitrification, 50 MGD	3b	2.1	1.4
6. Reduce METRO discharge to lake, process innovation for improved nitrification, 50 MGD	3c	1.8	1.1
7. Complete METRO bypass of lake	4a	0.4	0.4
8. Complete METRO bypass and 30% tributary TP reduction	4b	0.5	0.4

+ standard = 0.77 mgN/L.
* maximum margin of violation over the mid-May to mid-September interval.
**average margin of violation over the mid-May to mid-September interval.

scenario would eliminate violations of the T-NH_3 standard(s) for the upper waters of the lake (see subcase 4b of Fig. 7). The model was also used to determine the T-NH_3 concentrations in the METRO effluent that would be necessary to meet the standard for an in-lake (100%) discharge, for the critical tributary flow conditions of 1987. Effluent T-NH_3 concentrations of 2 mgN/L, during the colder late fall through winter interval, and 1 mgN/L, during the spring through early fall period, would be required to (just barely) avoid violation of the in-lake T-NH_3 standard. Achieving this level of nitrification during the cold months is problematic. For example, note the much higher concentrations that prevail at the existing Baltimore facility (Fig. 4d). We are not aware of a large scale operating domestic wastewater facility that routinely achieves this level of nitrification in the colder climates of the United States.

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There are several salient features of the predicted improvement in oxygen resources that would result from diversion. The rate of oxygen depletion would be reduced, the onset of anoxia would be delayed (Fig. 7b), and the depth interval of anoxia (extending from the lake bottom upward; see Gelda and Auer 1996) would be reduced for much of the summer. However, almost the entire hypolimnion would be anoxic by late summer (Fig. 7c). It should be noted that other mesotrophic lakes of similar mean depth in central New York have hypolimnia that become anoxic by late summer, as a result of the relatively small size of these hypolimnia (e.g., Effler et al. 1989, Effler and Rand 1978). The most profound improvement in oxygen resources from diversion of METRO would be the elimination of the lake-wide violations of the DO standard(s) in the upper waters of the lake during the fall mixing period (Fig. 7a). This would eliminate the exodus of fish to the Seneca River that has been documented during these depletion events (Tango and Rigler 1996).

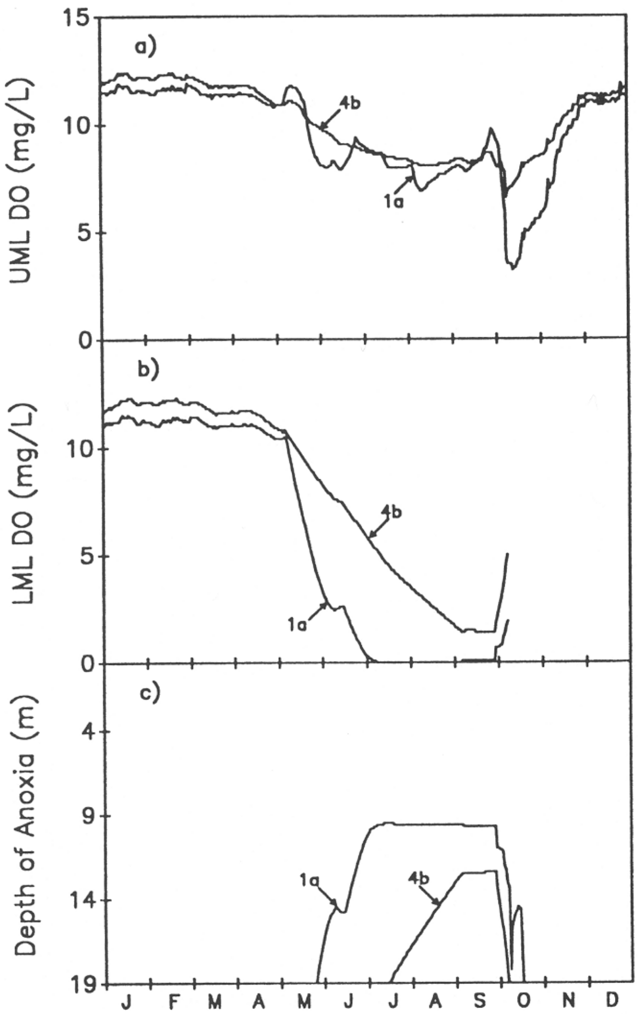

Figure 7.–Predicted seasonal distributions of DO in Onondaga Lake for two selected sub-cases (1a, 4b): (a) upper mixed layer (UML), (b) lower mixed layer (LML), and (c) upper bound of anoxia.

tributary loading will probably also be necessary to reach the TP goal. Expensive programs to reduce tributary TP loading should not be considered without elimination of the METRO input, because of the relatively small contribution the manageable portion of the tributary load makes to the existing total load, and the insignificant response predicted.

Simulations for METRO diversion scenarios utilize estimates of future steady-state sediment fluxes, but do not predict the interim responses or the time necessary to reach the steady-state conditions. The development of a mechanistic sediment model(s) for Onondaga Lake is recommended, that would be capable of simulating the time course of change of key sediment exchange processes in response to major reductions in loading and trophic state.

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