Simulation of Operations and Water Quality Performance of Reservoir Multilevel Intake Configurations

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Abstract: A predictive framework is developed and applied to evaluate benefits of multilevel intake configurations in managing temperature (T_W) and turbidity ($C_{T,W}$) in water withdrawn from a water supply reservoir, Schoharie Reservoir, New York, that presently, has a single level intake. High values of T_W occur in late summer for the reservoir in major drawdown years, and high $C_{T,W}$ levels occur irregularly following runoff events. The framework, composed of a tested two-dimensional water quality model for temperature and turbidity linked to a heuristic optimization algorithm, supports automated selection of intake levels to meet user-specified operational goals. Multilevel intake configurations are demonstrated to avoid exceedences of a State discharge standard (21.1°C) for T_W for the conditions of a critical historic year, through a strategy of withdrawal of warmer upper layers through early summer and subsequent blending with cooler lower layers as necessary, at both the existing intake site and a deeper down-reservoir location. The adequacy of the existing intake site is challenged for this critical year if a conservative lower T_W standard is set to accommodate the effects of model uncertainty. Amelioration of high $C_{T,W}$ values is demonstrated for multilevel intake configurations. The operation of a multilevel intake facility in the reservoir would result in a shallower epilimnion and metalimnion in many years, and summer surface temperatures would be lower in major drawdown years. The modeling approaches used in this analysis are generally applicable to support evaluations of multilevel intake configurations for other water supply lakes and reservoirs.

DOI: 10.1061/(ASCE)0733-9496(2007)133:1(78)

CE Database subject headings: Simulation; Water quality; Reservoirs; Intakes; New York.

Introduction

The demands on water quality of releases and withdrawals from water supply reservoirs and lakes are often more diverse and stringent where additional uses and related requirements must be met. Locations of water supply intakes and releases are important determinants of water quality for these outflows for deep stratifying systems. Water quality patterns in time and space within these systems are of concern if goals are to be met continuously. These patterns may reflect short-term drivers, such as runoff events (e.g., Effler et al. 2006; Gelda and Effler 2006b) and chemical spills (e.g., Chung and Gu 1998), or seasonal transformations (Wetzel 2001), and they may have distinct signatures in horizontal or vertical dimensions (Martin and McCutcheon 1999).

Thermal stratification, a ubiquitous phenomenon in deep lakes and reservoirs (Wetzel 2001), results in major vertical differences in temperature seasonally in temperate climates. Further, it is widely acknowledged to be an important regulator of ecosystem metabolism, often causing wide vertical differences in several common metrics of water quality seasonally (Stefan et al. 1976; Martin et al. 1985; Effler and Owens 1996). Runoff events can represent special challenges to the water quality of lakes and reservoirs, as large quantities of turbidity-causing particles are often received over brief intervals (Young et al. 1988; Longabucco and Rafferty 1998). Particle enriched tributaries enter as turbid density currents during runoff events in many reservoirs (Martin and McCutcheon 1999). These inputs form turbid plumes within the water column (e.g., Effler et al. 2006), manifested as underflows (along the bottom) or interflows within stratified layers (Fischer et al. 1979; Akiyama and Stefan 1984; Martin and McCutcheon 1999). Spatial patterns of turbidity impacts from these events vary in response to the seasonality of the stratification regime as well as characteristics of the runoff event (Effler et al. 2006; Gelda and Effler 2006b).

Selection of intake and release locations in lakes and reservoirs need to reflect not only the quantity demands of the water supply, but also water quality concerns, and thus related patterns within the system over the time and space scales of interest and feedback effects from operations. The flexibility of multiple intake/release depths offer advantages for more continuously meeting water quality goals, by providing a means to avoid undesirable layers. Such configurations are widely implemented in water supply reservoirs and lakes (Martin and McCutcheon 1999). Strategies for operation of these facilities may reflect seasonality in quality goals and the stratification regime (e.g., Hanna et al. 1999), as well as responsiveness to much shorter term events. For example, a multiple depth withdrawal facility was installed at the Shasta Reservoir (California) dam to enhance the ability to maintain downstream water temperature (T, °C) for the winter run of Chinook salmon, while still meeting the other purposes of the reservoir (Hanna et al. 1999). Clearly, a reliable predictive model(s) is needed to represent the effects of various

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Note. Discussion open until June 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on June 9, 2005; approved on November 21, 2005. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 133, No. 1, January 1, 2007. ©ASCE, ISSN 0733-9496/2007/1-78–86/$25.00.

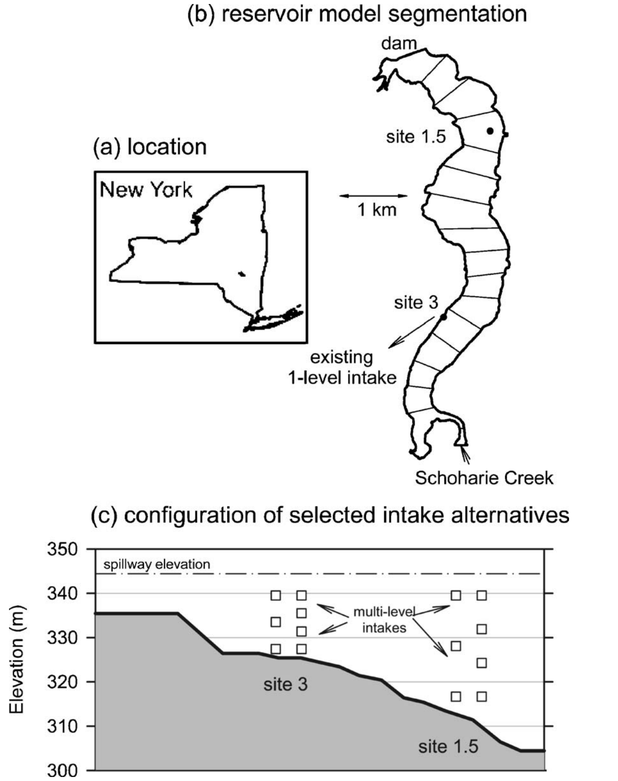

Fig. 1. Schoharie Reservoir: (a) location within New York; (b) map with locations of Schoharie Creek inflow, existing water supply intake, potential sites for multilevel intakes (1.5 and 3), and longitudinal model segments; and (c) vertical positions for four intake scenarios (Table 1)

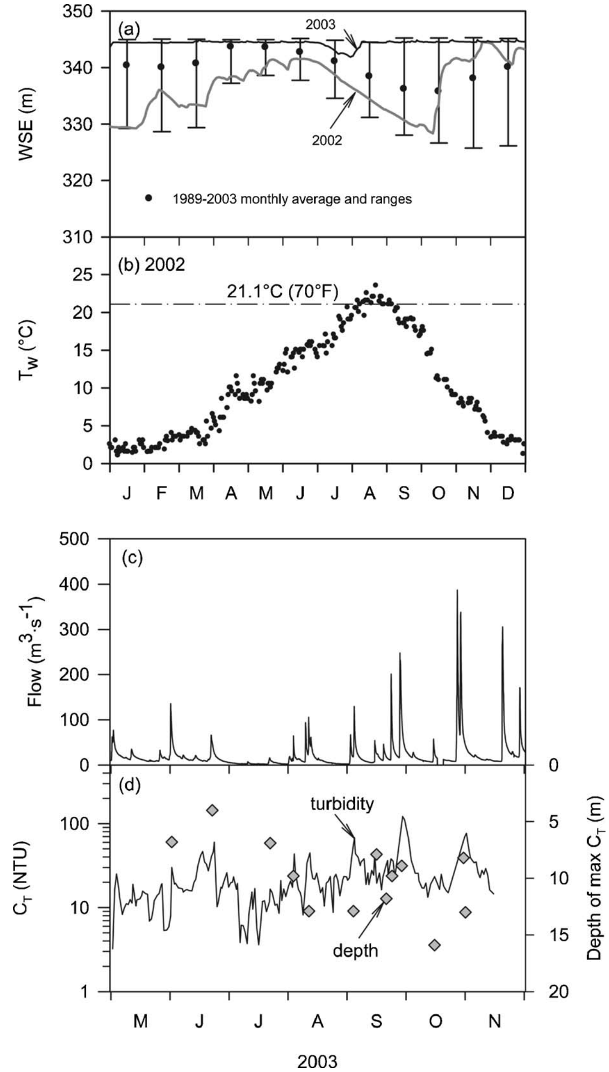

Fig. 2. Observations for Schoharie Reservoir: (a) WSE, monthly means and ranges for 1989–2003, with time series of daily values for 2002 and 2003; (b) time series of temperature of water withdrawn from reservoir (T_W) in 2002; (c) time series of daily flow rates of Schoharie Creek into Schoharie Reservoir over the May–November interval of 2003; and (d) time series of maximum turbidity from vertical profiles, and depths of maximum turbidity from vertical profiles following run-off events, for the May–November interval of 2003, at Site 3

drivers and operations, and to evaluate various withdrawal/release positions and feedback effects on reservoir conditions for operation scenarios.

The goal of this paper is to document the development and application of a predictive framework to evaluate the benefits of multilevel intake configurations in managing water quality in the withdrawal from a water supply reservoir. A tested two-dimensional water quality model for T (Gelda and Effler 2006a), and turbidity (C_T; Gelda and Effler 2006b) is applied for a stratifying water supply reservoir impacted by drawdown and turbid density currents, to evaluate the effects of multiple level intake and site alternatives on related features of water quality. The analysis is supported by the development of a heuristic optimization protocol that is linked to the water quality model. The overall linked framework, that supports automated determination of intake levels for use to meet goals, is applied to evaluate the efficacy of various combinations of number and position of intake levels and the feedback effects of such operations on the reservoir's stratification regime. The framework has broad applicability for water supplies that have, or are contemplating, multilevel intakes.

System Description

Schoharie Reservoir is located (latitude 42° 23′N; longitude 74° 27′W) in southern New York, approximately 190 km from New York City [NYC, Fig. 1(a)]. This reservoir, initially filled in 1927, is part of a network of 19 reservoirs that supplies drinking water to nine million people in the NYC area. The reservoir is 8 km long and lacks dendritic features [Fig. 1(a)]. When full, the impoundment has a volume of 79×10^6 m^3, a surface area of 4.6 km^2, and a maximum depth of 41 m. However, its morphometric features often vary seasonally associated with the drawdown of the reservoir's surface [e.g., water surface elevation (WSE), Fig. 2(a)], in response to withdrawals for the water supply [single level intake, Fig. 1(a)] exceeding inputs from the watershed (815 km^2). The greatest drawdown is usually observed in September and October. The substantial interannual variability in WSE [Fig. 2(a)] is driven by natural variations in runoff. The reservoir's major tributary, Schoharie Creek, drains 75% of the watershed, and enters at the southern end. The impoundment flushes 10.1 times per year on average, on a completely mixed basis and has a dimictic stratification regime, though its features (e.g., duration of stratification) vary year-to-year in response to the extent of drawdown (Gelda and Effler 2006a). Only minor longitudinal differences in temperature (T; °C) occur (Gelda and Effler 2006a). The intake is located at an elevation of 321.1 m (centerline; 23 m below full reservoir surface). However, as a result of extensive local sedimentation, withdrawal below 326.9 m (i.e., 5.8 m shallower; Gelda and Effler 2006a) is no longer viable.

Schoharie is described as an upstream reservoir within the NYC system, as water withdrawn for the water supply travels through a 29 km underground tunnel, then a stream, and two downstream reservoirs before delivery to the city. The intervening stream, Esopus Creek, supports a salmonid fishery. Related water quality concerns for the discharge of water withdrawn from the reservoir include temperature (T_W; °C) and turbidity ($C_{T,W}$; NTU). Features of water quality concern addressed here remain unchanged over the length of the tunnel, thus the withdrawal conditions for T_W and $C_{T,W}$ reflect the discharge to the stream. In major drawdown years, such as 2002 [Fig. 2(a)], T_W has exceeded the state regulatory standard of 21.1°C in late summer [70°F; Fig. 2(b)], because of the earlier withdrawal of the cooler hypolimnetic and metalimnetic waters via the single bottom intake (Gelda and Effler 2006a).

The reservoir suffers from increased C_T levels following runoff events [Figs. 2(c and d)] associated with terrigenous inorganic sediment inputs from the tributaries, primarily Schoharie Creek (Effler et al. 2006). The turbid waters enter within plunging density currents from this tributary over the summer and early fall, forming an underflow in up-reservoir areas and interflow down reservoir [Fig. 2(d); Effler et al. 2006], because of the cooler temperatures of the Schoharie Creek relative to the reservoir. Presumably this material enters the upper layers as a buoyant overflow earlier in the year. These runoff event driven impacts generally diminish along the axis of the reservoir, and with time (e.g., preevent turbidity levels approached within a week; Effler et al. 2006). In contrast to the T_W issue, more critical conditions for $C_{T,W}$ are observed in high runoff years, such as 2003 [Fig. 2(c)], when the reservoir remains more full [Fig. 2(a)]. A proposed regulatory limit is to avoid the discharge of reservoir water with a $C_{T,W}$ value that exceeds the ambient Esopus Creek conditions upstream of the discharge by more than 15 NTU.

Modeling

Description of Models

Hydrothermal/Transport Submodel

The computer code adopted for the reservoir was the hydrothermal/transport submodel of CE-QUAL-W2 (W2/T), a dynamic, laterally averaged, two-dimensional (longitudinal and vertical) model (Edinger and Buchak 1975; Cole and Wells 2002). The need for the two-dimensional capabilities of W2/T is driven primarily by the substantial longitudinal differences in C_T that occur along the reservoir's main axis following runoff events (Effler et al. 2006). The model is based on the finite-difference solution of partial differential equations for laterally averaged fluid motion and mass transport. The equations of the model that describe horizontal momentum, free water surface elevation, hydrostatic pressure, continuity, the equation of state, and constituent transport have been presented by Cole and Wells (2002), Chung and Gu (1998), and Gu and Chung (1998). The model assumes that vertical velocities are sufficiently small to allow the vertical

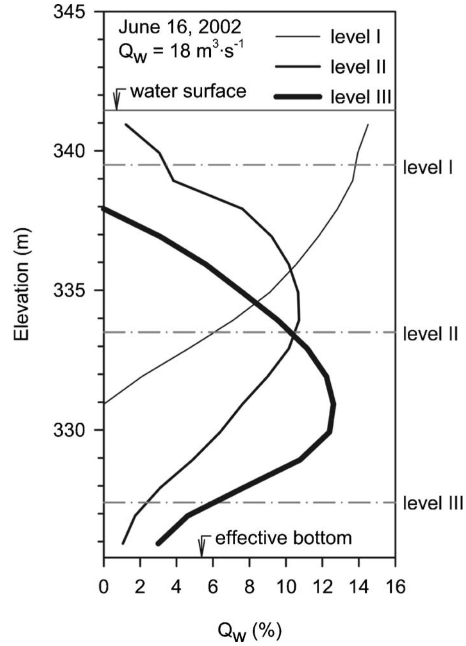

Fig. 3. Model simulations of vertical contributions to withdrawal flow (Q_W) for conditions of June 16, 2002, for three intakes (centerline positions shown), operating separately

momentum equation to be simplified to the hydrostatic equation. The model represents the reservoir in the form of a grid of cells consisting of longitudinal segments and vertical layers. The geometry of the computational grid is determined by the vertical layers, and average cross-sectional width. The Schoharie Reservoir model has 19 longitudinal segments (Fig. 1) and the vertical layers are 1 m thick. The heat budget of the model includes terms for evaporative heat loss, short-, and long-wave radiation, convection, conduction, and back radiation (Cole and Wells 2002). Required inputs include meteorological conditions, the attenuation coefficient for downwelling irradiance, and hydrologic information (inflows, outflows, and WSE). The model has six coefficients, that, with the exception of wind sheltering coefficient, generally do not vary substantially among most systems.

Features of outflow structures are also represented, including the spillway length, and depth(s) of the water supply withdrawal(s) and dam release(s). Withdrawals are effectively taken from a rather broad depth interval adjoining an intake (Martin and McCutcheon 1999), as represented by W2/T (Cole and Wells 2002). This is illustrated by model simulations (Fig. 3) for three different intake elevations (and depths) for the model segment containing the existing intake site, for the conditions observed for a selected day (June 16) in 2002, as vertical patterns of the contributions to the withdrawal flow rate (Q_W; $m^3\,s^{-1}$). These simulations represent the vertical effects across the entire model segment, rather than local, or near-field, conditions. These simulated vertical features of Q_W are important as, together with predicted profiles of water quality, they control the simulations of water quality in the withdrawal.

Two different time scales of performance of W2/T are important to represent the issues of concern: (1) seasonal, to quantify the thermal stratification regime and T_W, and (2) day-to-day, to describe the impacts of runoff events on $C_{T,W}$ levels. The development of data sets to drive the model and to specify patterns of state variables have been described elsewhere (Gelda and Effler 2006a). Gelda and Effler 2006a established that W2/T was an appropriate model to evaluate hydrothermal management issues for the reservoir, based on its validation for 15 consecutive years (1989–2003), a period that included wide ranges of drawdown. The model performed well in simulating the various features of the reservoir's stratification regime in each of the years, including the timing and duration of stratification, and the dimensions and temperatures of the layers. The model also performed well in predicting T_W and the periods of internal wave oscillations in stratified layers (Gelda and Effler 2006a). The model has also shown to simulate well patterns of special conductance (conservative tracer) imported by runoff events, including the entry and behavior of turbid density currents (unpublished). The model performed well in simulating both the short-term temporal and spatial patterns of this tracer associated with these events, that represented a wide range of runoff and related impacts on C_T levels in the reservoir (Effler et al. 2006).

Turbidity Model

A turbidity submodel, that adopts the beam attenuation coefficient at 660 nm ($\mathbf{c}_{660}$) as a surrogate of C_T (C_T=2.5 $\mathbf{c}_{660}$), has been developed and tested for Schoharie Reservoir (Gelda and Effler 2006b). The model, and related testing efforts, featured: (1) $\mathbf{c}_{660}$ as the state variable, rather than the systematically flawed gravimetric measure of suspended solids (disconnect between mass and light scattering features of particles); (2) comprehensive monitoring of tributary and meteorological forcing conditions and in-reservoir patterns of $\mathbf{c}_{660}$ following multiple runoff events (n=12) in 2003; (3) the above two-dimensional hydrodynamic model that simulated the transport of density currents; and (4) partitioning of $\mathbf{c}_{660}$ into slow and rapid "settling" fractions. The only kinetic process included was first order loss associated with settling. Related specifications include settling velocities for three fractions of $\mathbf{c}_{660}$, and partitioning of the fractions. The rapid "settling fractions" of $\mathbf{c}_{660}$ implicitly accommodate the effects of the operation of natural aggregation processes (Gelda and Effler 2006b).

The model performed well in simulating the timing and magnitude of $\mathbf{c}_{660}$ peaks in the reservoir soon after each runoff event, the distinct vertical and longitudinal patterns in this metric of C_T, the lessening of impact following events, and the dependence of the impact on the magnitude of the runoff event (Gelda and Effler 2006b). The framework and approach is expected to be transferable to many systems, though the complexities of sediment resuspension and three-dimensional transport may need to be addressed in certain waterbodies.

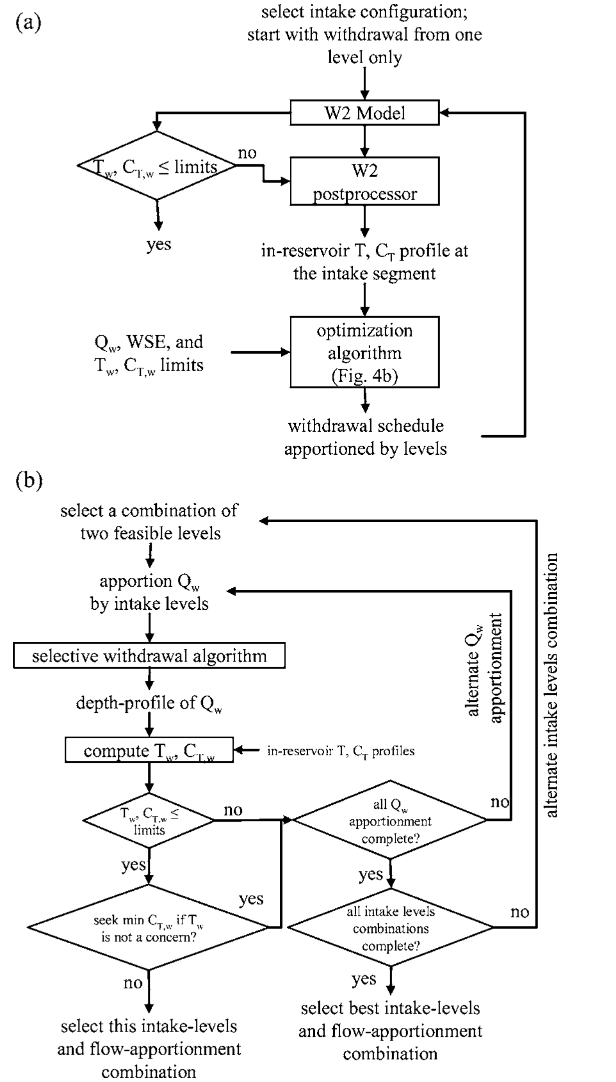

Fig. 4. Optimization for operation of multilevel intake facility: (a) linkage of two-dimensional water quality model and optimization algorithm; (b) heuristic optimization algorithm for blending of withdrawals from multiple intakes to meet T_W goal and minimize $C_{T,W}$

Optimization

An optimization framework [Fig. 4(a)] was adopted here, that links the reservoir simulation model with a heuristic operations algorithm [Fig. 4(b)], to evaluate the benefits of a multilevel intake structure on the quality of withdrawn water. The water quality features of interest in this case are T_W, and $C_{T,W}$. The optimization algorithm reflects a strategy of using warmer (epilimnetic) waters earlier in the year, saving the colder hypolimnetic waters for late summer withdrawal, to avoid exceeding a specified goal for T_W in late summer and fall [e.g., Fig. 2(b)]. Required specifications include a time series of Q_W that reflects historic observations or a scenario of interest, and T_W and $C_{T,W}$ goals [Fig. 4(a)]. Additional inputs include WSE and simulated vertical profiles of in-reservoir T and C_T, from the model segment containing the intake (model output). The algorithm proceeds day by day, determining the combination of withdrawal levels and flows that meet, if possible, the specified goals. The heuristic approach [Fig. 4(b)] has advantages over other optimization techniques, such as dynamic programming, including computational efficiency and ready linkage with a simulation model such as W2/T.

Initially the algorithm establishes the intake levels that are available [i.e., positioned below the WSE; Fig. 4(b)]. The desired Q_W is then apportioned among the available intake levels for withdrawal. Two adjoining intake levels are selected for withdrawal, moving downward in the water column. For example, for a four-level intake facility, intakes I and II are first selected (numbered according to shallowest, or highest elevation, as intake I, and deepest, or lowest elevation, as intake IV), consistent with the strategy of preserving the colder hypolimnetic water. High C_T values at these intake levels would force shifts to deeper intakes. The apportionment (blending) of Q_W for the selected levels is done progressively, starting with 100% from the upper level and 0% from the deeper level, with shifts in this partitioning (increments of 0.5%) as necessary to meet the specified goals

Table 1. Specification of Four Multidepth Configurations for Evaluation by Optimization Framework

Scenario[a]	Site	Number of levels	Elevation of intake levels (m)[b] I	II	III	IV	$C_{T,W}$[c] (%)
A	3	3	339.5	333.5	327.4	—	4.1
B	3	4	339.5	335.5	331.4	327.4	4.1
C	1.5	3	339.5	328.1	316.7	—	2.6
D	1.5	4	339.5	331.9	324.3	316.7	2.6
Baseline[d]	3	1	—	—	—	327.4	7.2

[a]See Fig. 1(a).

[b]Centerline, assuming 2.45 m height for intakes.

[c]Percent occurrences of turbidity greater than 15 NTU.

[d]Prevailing conditions, simulations according to Case 2 (conditions of 2003 with Q_W of 2002).

[Fig. 4(b)]. The relatively small size of the increments supports a "smooth" blending that reduces variations in T_W that could lead to irregular exceedences of the goal (e.g., Hanna et al. 1999).

The withdrawal algorithm is then used to calculate the effective withdrawal flow rate from each of the model layers (e.g., Fig. 3, for single intake operation), based on the combination of determined levels and flow apportionment [Fig. 4(b)]. This, together with the model simulations of in-reservoir profiles of T and C_T for the model segment containing the intake, results in predictions of T_W and $C_{T,W}$. The selection of intake levels and flows has a feedback effect on predictions of in-reservoir T and C_T patterns. Iterative analyses of operation scenarios are conducted as necessary to meet the specified withdrawal goal(s). A minimal impact is sought if the specified goal cannot be met.

Specifications for Model Applications

Application of the optimization framework [Fig. 4(a)], that links the reservoir simulation model with the described heuristic operations algorithm [Fig. 4(b)], is demonstrated here in an evaluation of multilevel intake alternatives. The matrix of model applications considers two cases of driving conditions (1 and 2), and four different scenarios (A through D) of multilevel intake configurations (Table 1). The first case (Case 1) uses the conditions of 2002, the year of second greatest drawdown and highest T_W of the 1989–2003 period (Gelda and Effler 2006a). The analysis for this case focuses only on meeting the T_W standard, as high $C_{T,W}$ was not an issue for this low runoff year. This arguably approaches a reasonable critical case for T_W to support related design evaluations, as it corresponds to actual historic observations. Maintenance of the observed Q_W time series, as part of this case, reflects protection of the reservoir's primary intended use as a water supply. The second case (Case 2), which additionally addresses $C_{T,W}$ (Fig. 4), is more synthetic in nature, within the context of the actual operations of this reservoir, because of the lack of monitoring data that adequately defined conditions for severe impacts on $C_{T,W}$. It adopts all the drivers and model inputs of 2003, a year with frequent, and sometimes major, short-term increases in reservoir C_T from runoff events [Figs. 2(c and d)], except for Q_W conditions. Withdrawals from the reservoir actually ceased (i.e., Q_W=0) for much of 2003 to avoid high turbidity contributions to the water supply. This was possible because water usually provided by this impoundment was instead supplied by other reservoirs in the system, under the high runoff conditions that prevailed in the region for that period. The second case adopts the same Q_W time series observed for 2002, offering a test of the use of multilevel intakes to avoid or ameliorate high $C_{T,W}$ levels. "Baseline" conditions for Case 2 adopt observed forcing conditions for 2003, including the single existing intake, with the exceptions of the invoked Q_W time series of 2002 and the resulting temporal pattern of WSE.

The development of model inputs, including the drivers for both 2002 and 2003, has been specified elsewhere (Gelda and Effler 2006a,b). The four scenarios considered here include two sites, one at the existing location (Site 3) and the other substantially down reservoir in a deeper area [site 1.5, Fig. 1(a)], and alternatives with either three (I through III) or four (I through IV) intake levels [Table 1; Fig. 1(b)]. All four scenario configurations (A through D) have a near-surface intake (I) at an elevation (centerline of 2.45 m high intake) of 339.5 m (Table 1). The deepest intake levels approach the reservoir bottom at the two locations, and remain unchanged for three-level versus four-level intake scenarios [Fig. 1(b); Table 1]. The intermediate intake levels are positioned such that distances between them are equal. The down-reservoir site has the potential attributes of diminished impact of runoff events on C_T levels (Effler et al. 2006) and increased access to the reservoir's capacity [e.g., Fig. 1(b)]. Additionally, the framework has been reapplied for 2002 for a lower target T_W=19.2°C, determined as the residual of the existing limit (21.1°C) and the root mean square error value (~1.9°C) of model predictions of T_W (Gelda and Effler 2006a). This is intended to reflect the potential effects of model uncertainty, such as might be included in design evaluations (e.g., safety factor) of potential multidepth facilities. The specified lower target value is highly conservative, as predictions of T_W were evenly distributed around observations (Gelda and Effler 2006a).

Results

Optimization for T_W, Case 1 (Conditions of 2002)

Time series of simulations of apportionments of Q_W and associated predictions of T_W are presented first for Case 1 (conditions of 2002); the corresponding time series of observed WSE is included for reference (Fig. 5). All three intake levels were predicted to be active at some time during the year for both three-level intake scenarios [A and C; Table 1; Figs. 5(a and c)] and all scenarios were successful in avoiding violations of the standard for T_W [e.g., Fig. 5(d)]. The timing of use of the various intake levels was highly dependent on WSE for this case.

The early use of the deepest level intake through January and into February for scenario A [Site 3, three-level intake; Fig. 5(b)] reflects the extensive drawdown of the reservoir surface at that time. Subsequent shifts in use of the various intake levels for this scenario, including the abrupt startup and subsequent discontinued use of the upper intake in early May, all tracked the dynamics of WSE [Fig. 5(a)], reflecting the use of the intake positioned highest in the water column. The upper intake was used solely for this scenario from early May through June [Fig. 5(b)]. Clear increases in T_W relative to the observations for 2002 were manifested over this interval [Fig. 5(d)], reflecting the effects of releasing epilimnetic waters instead of the cooler waters of the lower layers at Site 3. Blending, guided by the optimization algorithm, of relatively small amounts of Level II with the Level I withdrawal was necessary through early July to meet the T_W standard. Note that predicted T_W tracks the specified standard during this and other intervals of blending [Fig. 5(d)]. Drawdown eliminated access to Level I starting in early July. The attendant shift to

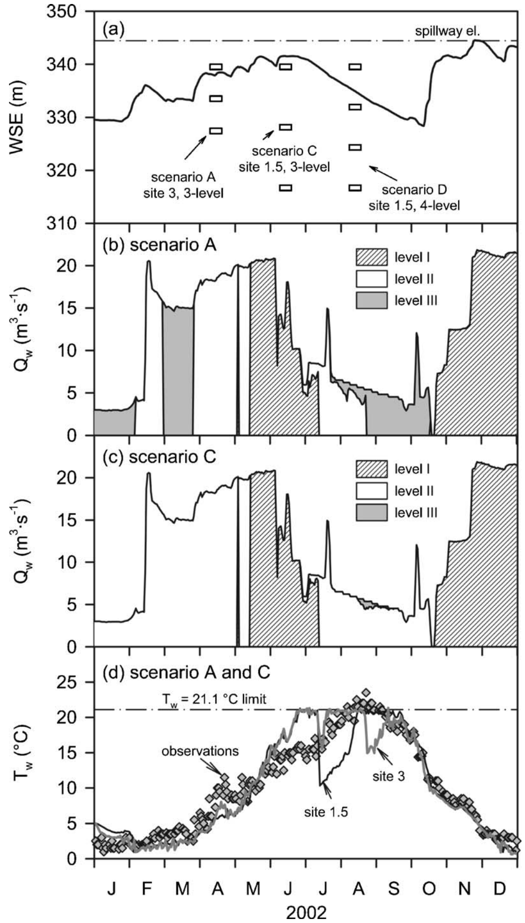

Fig. 5. Time series for Case 1 (conditions of 2002): (a) WSE, with vertical positions of intakes presented for multilevel intake scenarios; (b) Q_W (observed) and simulated apportionments for intake levels of Scenario A; (c) Q_W (observed) and simulated apportionments for intake levels of Scenario C; and (d) T_W, observations and model predictions for Scenarios A and C

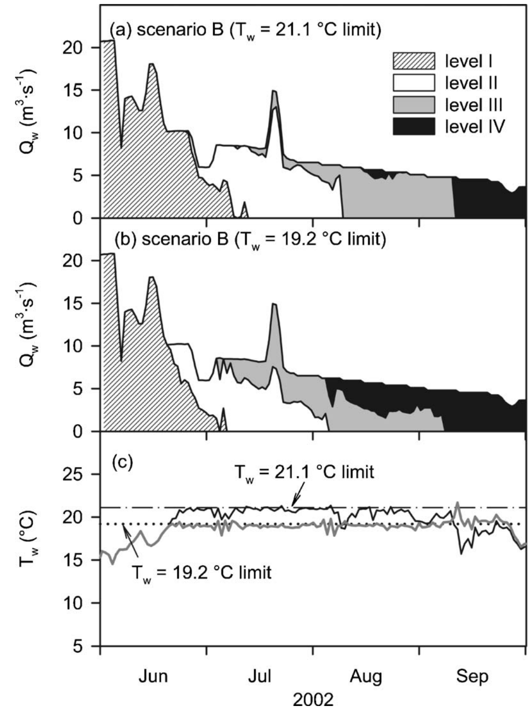

Fig. 6. Time series for Case 1, for conditions of June–September 2002: (a) Q_W (observed) and simulated apportionments for intakes of Scenario B, for a T_W limit of 21.1°C; (b) Q_W (observed) and simulated apportionments for intakes of Scenario B, for a T_W limit of 19.2°C; and (c) model predictions of T_W for Scenario B

Level II [Fig. 5(b)] was accompanied by a sharp decrease in T_W of ~5°C. Blending of withdrawals from intake Levels II and III became necessary for this scenario to meet the T_W standard starting in late July, and continued until late August when access to the middle intake level was eliminated by drawdown [Figs. 5(a and b)]. The abrupt shift to Level III (bottom) as the sole source of Q_W resulted in a second sharp decrease in T_W of ~5°C [Fig. 5(d)]. Exclusive use of this bottom level intake was required through mid-October (past the time when T_W values approached the standard), when the abrupt refilling of the reservoir [Fig. 5(a)] from high runoff allowed access to the upper level intake [Fig. 5(b)].

Certain features of the simulations for Scenario C (Site 1.5, three-level intake), an alternative that would position a multilevel intake facility in a deeper part of the reservoir [Fig. 1(b)], present interesting contrasts to those presented for the shallower site [Figs. 5(b and d)]. The middle Level (II) for this scenario met the entire Q_W demand through April. Thereafter, until late June, the apportionment according to levels did not differ from scenario A (Site 3, three-level intake). Smaller contributions from Level II were required in the blending interval of late June through early May for Scenario C (Site 1.5, three-level intake; Figs. 5(b and c)], associated with the colder (e.g., deeper) waters available at Level II for this scenario. This was also responsible for the even larger decrease in T_W (~10°C), compared to Scenario A [Site 3, three-level intake; Fig. 5(d)], when drawdown eliminated access to the upper level intake. Use of the deepest level intake is predicted only for about two weeks in late August [Fig. 5(c)] to avoid exceedences of the standard for T_W [Fig. 5(d)]; the contribution from the deep intake remained less than 15% over this interval. Intake Level II was used thereafter, until access to Level I was acquired with the rapid increase in WSE in late October.

The other two scenarios were also predicted to continuously meet the T_W standard, though, of course, there were differences in predicted time series of apportionments for these configurations. Differences in the temporal patterns of T_W were also predicted. For example, scenario D (Site 1.5, 4-level intake) resulted in a somewhat less severe decrease in T_W in mid-July (~8°C) compared to scenario C (site 1.5, 3-level intake), however, the added intake level included in this configuration was accompanied by a second major decrease in T_W (~10°C) in September.

The conservative selected margin of safety evaluated here for Case 1 (conditions of 2002), in the form of a T_W limit of 19.2°C, would require substantial changes in the timing and magnitude of blending [Figs. 6(a and b)], and would be a challenge for a multilevel intake facility at the shallower Site 3 [e.g., Scenario B; Site 3, four-level intake; Fig. 6(c)]. Sequential operation of all four levels was predicted for this scenario over the June–September interval for Case 1 (conditions of 2002), a period of largely progressive drawdown [Fig. 5(a)]. Contributions by deeper level intakes were shifted earlier and required greater relative inputs from these withdrawals, for all the intake scenarios for the lower T_W limit. Corresponding predictions of T_W increased above this limit for a substantial portion of September, and rose above the 21.1°C limit for a single day, for Scenario B [Site 3, four-level intake;

Fig. 6(c)]. Similar patterns of T_W were predicted for Scenario A (Site 3, three-level intake) for this lower T_W limit. This behavior reflects the limitations Site 3 has with respect to access to the deeper layers of the reservoir. The lower T_W limit of 19.2°C was successfully met for the Site 1.5 scenarios.

The deepest level intake was not used for Scenario D (Site 1.5, four-level intake), consistent with the greater access to the reservoir's capacity at this deeper location [Fig. 1(b)]. Additional analyses conducted to assess the potential for increased Q_W over the drawdown interval of July through October indicate that such an increase may have been supportable by this intake configuration. However, this potential needs to be further evaluated within the context of the available hydraulic head (Gannett Fleming & Hazen and Sawyer 2004).

Optimization for T_W and $C_{T,W}$, Case 2 (Conditions of 2003 with Q_W of 2002)

Time series of simulations of WSE [Fig. 7(a)], apportionments of Q_W [Fig. 7(b)] for Scenario A (Site 3, three-level intake), T_W [Fig. 7(c)] for Scenario A, and $C_{T,W}$ for Scenarios A [Fig. 7(d)] and C [Site 1.5, three-level intake; Fig. 7(e)] are presented for the May–November period for Case 2. Use of the upper level intake was predicted for most of the period, except for brief intervals in September and November and most of the month of October [Fig. 7(b)]. This was made possible by the nearly full reservoir conditions that prevailed [Fig. 7(a)]. Operating according to this scenario would have substantially increased T_W through August compared to the baseline simulations, approaching, but not exceeding, the standard in August. This reflects influences of the rather broad depth interval the intake draws upon (e.g., Fig. 3), and the somewhat cooler temperatures (e.g., compared to 2002) that prevailed in the epilimnion in late summer associated with meteorological conditions. The sharp, closely spaced, oscillations and decreases in predicted T_W starting in late September [Fig. 7(c)] reflect short-term shifts to the deep level (III) intake for Scenario A (Site 3, three-level intake) to minimize the impact of high $C_{T,W}$ from runoff events.

Diminishment of high $C_{T,W}$ levels was predicted for the multidepth withdrawal scenarios [e.g., Figs. 7(d and e)]. In general the predicted peak values of $C_{T,W}$ at Site 3 [Fig. 7(d)] associated with runoff events, for both baseline and scenario simulations, were in most cases substantially diminished from the observed water column C_T maxima [Fig. 2(d)]. This reflects the effects of the broad depth interval contributing to Q_W (Fig. 3), that at times was large relative to the depths impacted by turbid density currents, as well as the systematic displacement from the depths of maximum impact [Fig. 2(d); Effler et al. 2006; Gelda and Effler 2006b]. Only modest benefit was predicted for Scenario A (Site 3, three-level intake), relative to baseline conditions, for $C_{T,W}$. Further, this multilevel intake scenario did not eliminate the predicted exceedences of the turbidity goal caused by the major runoff events of late September and October [Fig. 7(d)]. Levels of $C_{T,W}$ were predicted to be lower for Scenario C (Site 1.5, three-level intake), associated with the benefits of attenuated impact of runoff events at Site 1.5 (Effler et al. 2006; Gelda and Effler 2006b) and perhaps the wider spacing of intake levels [Fig. 1(b)] that improves avoidance of turbid interflow depth. Values of $C_{T,W}$ were predicted to exceed 15 NTU 4.1% of the simulation interval for Scenario A (Site 3, three-level intake), compared to 7.2% for the baseline conditions (Table 1). Exceedences were reduced to 2.6% of the interval for Scenario C (Site 1.5, three-level intake). Increasing the number of intake levels from three to four did not influence this metric of performance at either of the locations (Table 1).

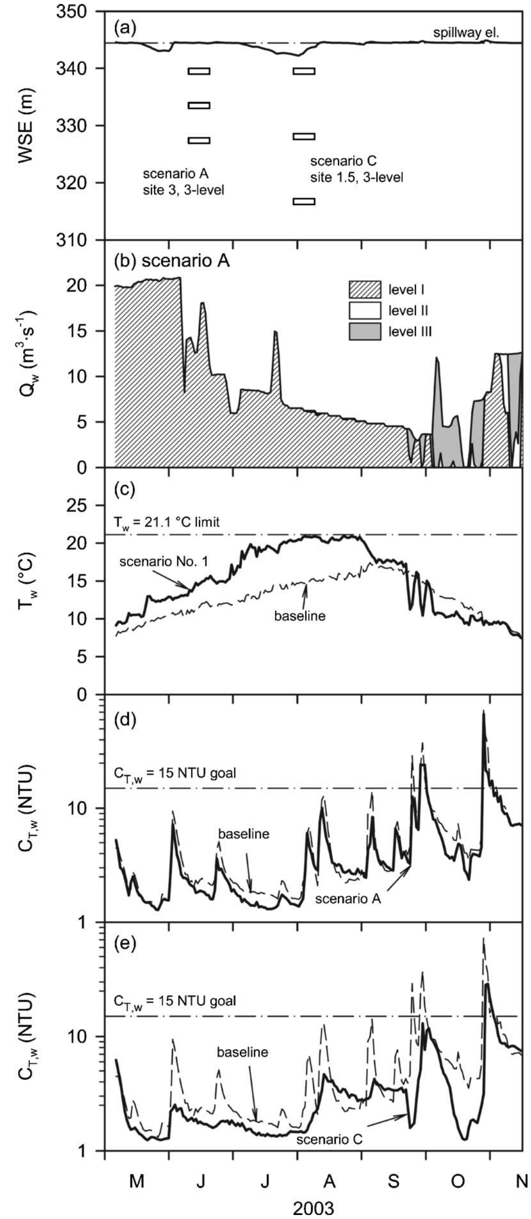

Fig. 7. Time series for Case 2 (conditions of 2003 with Q_W of 2002): (a) baseline simulation of WSE, with vertical positions of intake levels presented for Multilevel intake scenarios; (b) Q_W observed in 2002, with simulated apportionments for intakes of Scenario A; (c) model predictions of T_W for Scenario A and baseline conditions; (d) model predictions of $C_{T,W}$ for Scenario A and baseline conditions; and (e) model predictions of $C_{T,W}$ for Scenario C and baseline conditions

Impacts on Reservoir's Stratification Regime

The impact of the implementation of a multilevel intake facility on the reservoir's stratification regime is illustrated here for the intake configuration of Scenario A (Site 3, three-level intake) for Case 1 (conditions of 2002). The presented simulated temperature patterns are for a deep water model segment that contains Site 1.5. Isotherms are presented for Case 1 for prevailing [i.e., single

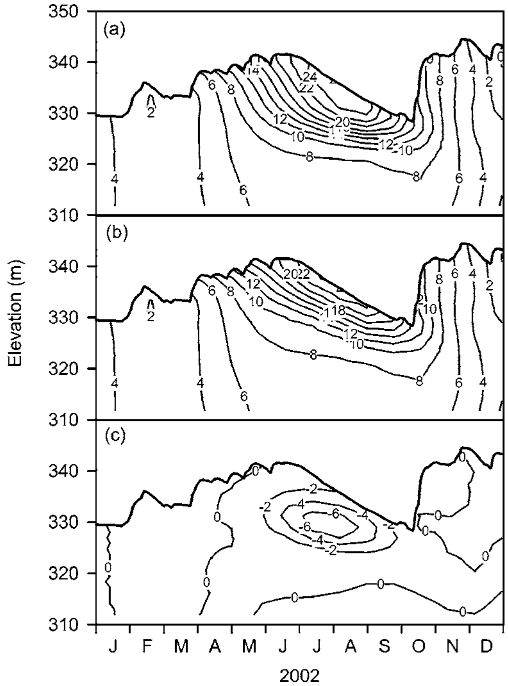

Fig. 8. Simulated isotherms for Site 1.5 for Case 1 (conditions of 2002): (a) for existing single level intake; (b) for multilevel intake Scenario A; and (c) residuals for existing single level intake and Scenario A (negative values depict temperature decreases from existing intake conditions)

intake; Fig. 8(a); Gelda and Effler 2006a] and Scenario A [Site 3, three-level intake; Fig. 8(b)] operations. The patterns were essentially the same in fall, winter, and early spring, and the timing of the onset of stratification and fall turnover was largely unaffected. The primary differences, as depicted here by the residuals of the isotherms of these two simulations [Fig. 8(c)], were manifested in the upper 5 to 10 m of the water column over the June to September interval. These layers were predicted to be cooler, by as much as 6 °C, for the multilevel intake scenario, and surface temperatures in August and September were predicted to be ~2 °C lower [Fig. 8(c)]. These substantial differences primarily reflect the reduced vertical dimension(s) of the epilimnion and the upward shift of the position of the metalimnion [Figs. 8(a and b)], and secondarily the generally lower temperature of the upper layers. Impacts were reduced for the nearly full reservoir conditions of Case 2 (conditions of 2003 with Q_W of 2002).

Discussion

Predictive Framework Capabilities

The predictive framework developed here, that linked a two-dimensional water quality model with an optimization algorithm, was successfully applied to identify an array of scenario multilevel intake configurations and operating schedules that would avoid exceeding a State discharge standard for T_W. The approach is believed to be broadly applicable where similar issues prevail. Similar capabilities to guide release strategies for a constructed multidepth facility to meet downstream temperature goals were reported by Hanna et al. (1999) for Shasta Reservoir. In that study an optimization program was coupled to W2/T, though details of the program were not described. Increments of outflow were large (10%) compared to those adopted here (0.5%), and the optimization considered temperature only. Their large Q_W increments were probably responsible for the greater variations bounding the target temperatures compared to those presented here (e.g., Figs. 5–7), Forty iterations were required in that application (Hanna et al. 1999) to meet the target temperature, compared to four, or less, encountered in this analysis. The framework presented here also supports simulations of the effects of operation of multilevel intake facilities on a reservoir's stratification regime and patterns of turbidity. This framework could easily be modified to meet more temporally refined T_W goals (seasonal; e.g., Hanna et al. 1999), while continuing to ameliorate high $C_{T,W}$ occurrences and depicting impact on the reservoir's stratification regime. The addition of other water quality parameters is limited only by the model's capabilities with respect to additional state variables and the availability of driver information to support case definition.

The successful scenarios identified also offer a reasonable margin of safety for meeting the T_W standard, within the context of potential uncertainties in model performance. However, the existing intake site could be challenged for a multilevel intake facility, for highly conservative margin of safety specifications, as demonstrated here. A potential for modest increased water delivery (Q_W), while continuing to meet the T_W standard, was indicated for the drawdown interval of 2002 for a deep water site (Site 1.5). However, this potential benefit needs to be tempered by other factors that include limited available hydraulic head and large cost for construction of an intake facility at that site (Gannett Fleming & Hazen and Sawyer 2004).

Though the existing single level intake configuration can result in seasonal exceedences of a T_W standard, prevailing temporal patterns of T_W [e.g., Fig. 2(b)] do not include the abrupt decreases predicted for the multilevel intake scenarios [e.g., Fig. 5(d)]. The potential impacts of these T_W decreases on stream temperature and the fishery need to be considered. A potentially valuable perspective is to evaluate these impacts within the context of natural variations in temperature presently experienced by the stream. The magnitudes of these abrupt decreases can probably be reduced by increasing the number of intake levels and changing the operating strategy embedded in the heuristic optimization (e.g., commence blending earlier as intake depth is approached during drawdown).

The presented model analysis is more conclusive with respect to temperature than for the turbidity issue, because of the limited C_T data to specify conditions for a wide range of runoff events during which active withdrawal occurs. The irregularity of runoff events and flexibility of operations within NYC's multiple reservoir water supply (e.g., taking the reservoir out of service for much of 2003) challenge the easy remedy of this problem. Continued monitoring of patterns of C_T in the primary tributary and within the reservoir for runoff events will contribute to the formation of additional cases to evaluate the potential benefits of multilevel intake configurations for the turbidity issue. Modest benefits were demonstrated for Case 2 (conditions of 2003 with Q_W of 2002) analysis presented here. It is likely that greater relative benefit would be demonstrated for summer events, when turbidity plumes would be more vertically confined (e.g., metalimnion; Effler et al. 2006), rather than the fall events embedded in Case 2.

Effects on Reservoir Water Quality, and Management Perspectives

The magnitude of Q_W is large enough to influence the heat budget of the reservoir, particularly in major drawdown years. Moreover, the operation of a multilevel intake facility would substantially alter the reservoir's stratification regime in summer (Fig. 8). Accordingly, the heat sources and mixing process that prevail during summer would not match the volumetric loss of relatively warmer waters from the uppermost available intake (Fig. 8). The predicted changes in the relative volumes of the stratified layers of the reservoir could influence the concentrations of phytoplankton in the epilimnion (Stefan et al. 1976), the rate of oxygen depletion in the hypolimnion (Burns 1995) and the vertical position of turbid plumes following runoff events (Effler et al. 2006).

A multilevel intake facility is one of the three alternatives that have been identified as potentially feasible and effective for improving the quality (T_W and $C_{T,W}$) of water withdrawn from Schoharie Reservoir; the others are an in-reservoir baffle to promote deposition of particles received from Schoharie Creek, and modification of reservoir operations (e.g., timing of withdrawal). The potential advantages of the deeper down-reservoir location (Site 1.5) for a multilevel intake facility (e.g., perhaps increased capacity) would only be achieved at great cost. Preliminary estimates indicate a facility at Site 1.5 would cost $\sim$ \$160 million more than at Site 3. Much of the difference would be associated with tunneling costs ($\sim$3 km long) to connect with the existing tunnel that carries the withdrawal (Gannett Fleming & Hazen and Sawyer 2004).

The predictive framework developed and demonstrated here will continue to serve as an invaluable tool to guide ongoing evaluations of multilevel intake alternatives to meet water quality goals for this reservoir. It may be desirable to evaluate a wider range of scenarios than addressed here. Updates of applications of the framework are recommended when improvement in a case(s) critical for $C_{T,W}$ can be developed from future detailed monitoring. Additional analyses could also identify intake configuration and operating strategy combinations that would minimize the abrupt reduction in T_W associated with drawdown.

Acknowledgments

Funding of this study was provided by the New York City Department of Environmental Protection. This is contribution No. 242 of the Upstate Freshwater Institute.

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