QEA
Quantitative Environmental Analysis, LLC
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Final

Phase 2 Report

Three Rivers Water Quality Model

Prepared for:

Onondaga County Department of
Water Environment Protection
Syracuse, NY

Onondaga Lake Cleanup Corp.
Syracuse, NY

Prepared by:

Quantitative Environmental Analysis, LLC
Liverpool, NY

August 2005

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Job Number:

ONOsen:227

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EXECUTIVE SUMMARY

As part of an overall objective to assess the assimilative capacity of the Seneca River and guide management decisions regarding the potential diversion of the Syracuse Metropolitan Wastewater Treatment Plant (Metro) effluent to the Seneca River, Onondaga County developed a new water quality model of the Three Rivers System. The overall objective of this modeling effort was to develop a management tool to aid the County in complying with the Amended Consent Judgment (ACJ; Section 1.1.1) and facilitate the future development of Total Maximum Daily Loads (TMDLs) for oxygen demanding substances within the Seneca River. Ultimately, the dynamic water quality model of the Three Rivers System presented herein will be linked with the Onondaga Lake watershed model under development by the U.S. Geological Survey (USGS) and the Onondaga Lake water quality model to be developed by the County. Both the watershed and lake models are being funded by the Onondaga Lake Partnership (OLP). The watershed, lake, and river models will be integrated into a water quality management tool for the entire system. This tool will be the principal means by which water quality managers will assess the consequences of diverting all or a portion of the Metro effluent from Onondaga Lake to the Seneca River. Additionally, this framework will be used to update ammonia and phosphorus TMDLs developed for the lake in 1997 and develop the river dissolved oxygen TMDL.

This report documents the development, calibration, and preliminary confirmation of the Three Rivers Water Quality Model (TRWQM). This report was prepared by Quantitative Environmental Analysis, LLC (QEA) on behalf of Onondaga County, with support from Drs. Raymond Canale and Steven Chapra of EnginComp Software, Inc., and Dr. William Walker, Jr. of Concord, MA. A draft of this report was prepared in January 2003 for a peer review commissioned by the OLP and coordinated by the USGS and the Onondaga Lake Cleanup Corporation. A report of the peer reviewers’ findings was issued in April 2003 and is included as an appendix to this report. Recommendations made by the peer review panel are reflected in this final report and summarized in an appendix as well.

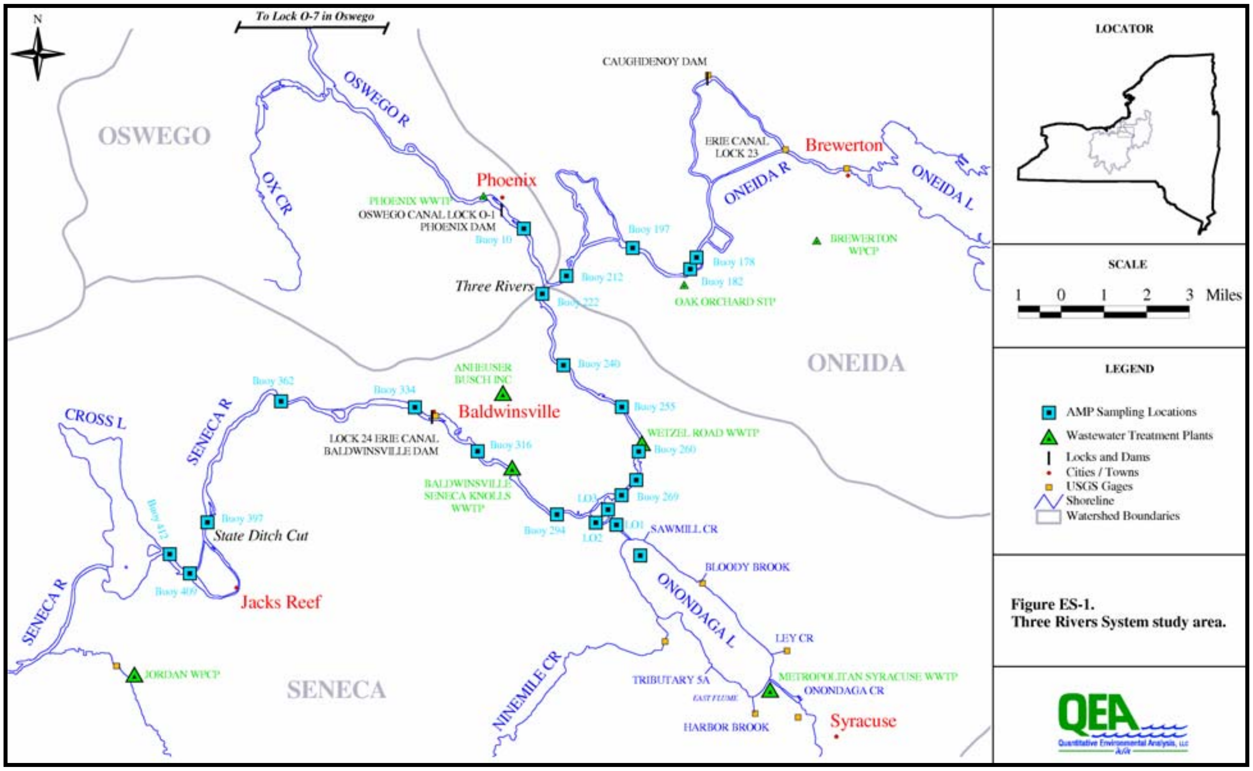

Figure ES-1. Map of the Three Rivers model domain and environs depicting Onondaga County's Ambient Monitoring Program sampling stations, USGS flow monitoring stations, and wastewater discharges.

ES.1 DESCRIPTION OF THE SYSTEM

The study area consists of a 36-kilometer stretch of the Seneca River, from Cross Lake downstream to the Three Rivers Junction, the Oneida River downstream of Caughdenoy Dam to Three Rivers Junction, and the Oswego River to the Phoenix Dam (Figure ES-1). The Seneca River receives water from two highly productive water bodies, Cross Lake (upstream of the study area) and Onondaga Lake (25 kilometers downstream of Cross Lake). Additionally, the system receives discharges from four wastewater treatment facilities (Anheuser Busch, Inc. and Onondaga County's Baldwinsville/Seneca Knolls, Wetzel Road, and Oak Orchard WWTPs; Figure ES-1). The Seneca River, NY is on the 1998 New York State's 303(d) list of impaired water bodies for non-attainment of dissolved oxygen criteria. The 26-kilometer segment of the Seneca River from Cross Lake to the Onondaga Lake outlet is one of the State's highest priorities for TMDL development -- a TMDL for oxygen demanding substances is scheduled for completion in 2007. In addition to TMDL development, engineering evaluations are being performed to assess the feasibility of diverting the 85 MGD Syracuse Metro WWTP effluent from Onondaga Lake to the Seneca River. Both the Metro diversion project and the TMDLs are complicated by a number of system characteristics, including:

- Interaction with Onondaga Lake. Because of hydraulic controls located both upstream (Baldwinsville Dam) and downstream (Phoenix Dam) of the lake's outlet, flows within the outlet may be into the river, into the lake, or bi-directional, with relatively dense lake water flowing into the river in the bottom of the channel and river water flowing into the lake in the upper layers of the channel (Swanson et al. 1994).
- River Stratification. Because of its higher salinity and lower temperature, relatively dense Onondaga Lake water that enters the Seneca River tends to plunge and form a relatively stable layer for several kilometers downstream, and even a few kilometers upstream (Effler et al. 1997). Circulation in this region is further complicated by the suspected additional presence of naturally saline groundwater seeps into this region of the river (Kappel 2004).
- Zebra Mussels. Between 1991 and 1993, the Seneca River was invaded by zebra mussels, an exotic bivalve originally from the Caspian Sea that filters particulates out of the water column for food and consumes oxygen during respiration (Karatayev et al. 1997). The most direct impact of zebra mussels in the Seneca River with respect to the TMDL and Metro diversion is the reduction in assimilative capacity due to depletion of dissolved oxygen.

To capture the complexity of the system and to guide decisions regarding the Metro diversion and the dissolved oxygen TMDL calculations, a mechanistic, dynamic water quality model of the Three Rivers System was developed. The model documented herein is the first mechanistic model that incorporates, in an integrated dynamic framework, state-of-the-science water quality kinetics, sediment diagenesis and nutrient cycling, as well as zebra mussel growth and nutrient cycling. Furthermore, the model has been developed and calibrated with an unusually extensive data set, including six years of Onondaga County's monitoring data covering widely ranging flow conditions, as well as a large suite of site-specific studies focused on hydrodynamics, individual water quality processes, sediment impacts, and zebra mussel growth and nutrient cycling. Finally, model performance has been assessed using probabilistic metrics directly related to water quality goals.

ES.2 MODELING FRAMEWORK

The model framework consists of four component submodels describing hydrodynamics, water quality kinetics, zebra mussel growth, and sediment fluxes.

ES.2.1 Hydrodynamics

The USEPA-supported model Environmental Fluid Dynamics Code (EFDC; Hamrick 1992) was used to simulate hydrodynamics. A two-dimensional, laterally-averaged numerical grid was used to simulate longitudinal and vertical variations in stage height, current velocity, and the transport of salinity, temperature, and water quality constituents. The model included 113 longitudinal cells, with 10 vertical layers. Daily net flows from Onondaga Lake to the Seneca River were estimated based on a lake-wide water balance (OCDWEP 1999; Walker 1996). Bidirectional flow in the outlet was approximated using a numerical algorithm relating flow into and out of the lake to the Seneca River flow measured at the Baldwinsville USGS gauging station, while honoring the net flow out of the lake calculated by the water balance, as well as observations of river water exchange with the lake (Naumann 1993).

ES.2.2 Water Quality

The water quality kinetics used in the model are an expanded version of those used in QUAL2E (Brown and Barnwell 1987). The algorithms incorporate phytoplankton growth, death, and respiration; reaeration; decomposition of particulate organics to dissolved organics and inorganic nutrients including nitrogen and phosphorus; nitrification; and settling of particulates.

ES.2.3 Sediments

A new sediment flux submodel framework was developed, based on the work of DiToro et al. (1990), DiToro and Fitzpatrick (1993), Cerco and Cole (1995), and DiToro (2001). The model consists of two sediment layers: Layer 1, the upper layer, is aerobic, and Layer 2, the lower layer, is anaerobic. Sediment oxygen demand and nutrient fluxes are modeled as diffusive exchange with the water column, and are coupled, through mass balances, to the depositional flux of organic matter from the water column.

ES.2.4 Zebra Mussels

A new zebra mussel submodel framework was developed for this work. This framework conserves the masses of carbon, nitrogen, phosphorus, and oxygen in computing zebra mussel metabolism and growth. The model accounts for seasonal and spatial differences in metabolism and growth in response to changing temperature, phytoplankton stocks, and dissolved oxygen resources. The zebra mussel submodel is constrained by site-specific measurements of filtration and respiration rates (Beak 2000b), literature-derived relationships describing pseudofeces and feces production, specific dynamic action, reproduction and site-specific size distribution data. The model: 1) includes a physiological component that computes the carbon balance for individual mussels (filtration, pseudofeces production, respiration, excretion, and growth); 2) incorporates changes in the numbers of mussels throughout the growing season; and 3) is fully integrated into the dynamic water quality model.

ES.2.5 Boundary and Initial Conditions

The model simulates the periods from May 1 to November 1 of a given year. Constituent concentrations at the upstream boundary are defined by data collected at Buoy 412 (Figure ES-1). Constituent concentrations entering from Onondaga Lake were based on bi-weekly data collected in the lake outlet channel. Flows and constituent concentrations associated with the four WWTP discharges located within the study area were based on monitoring data. Initial zebra mussel densities and weights on May 1 of a given simulation year were based on 1999 measurements, as adjusted by calibration.

ES.3 MODEL CALIBRATION AND CONFIRMATION

ES.3.1 Hydrodynamics

The hydrodynamic submodel was calibrated by comparing predicted and observed salinity and temperature at several locations for the period from May to October 1995. Model confirmation involved May-October hydrodynamic simulations for six years: 1994 and 1996-2000. No parameters were adjusted during model confirmation. Hydrodynamic results for 1997 and 2000 are shown in Figure ES-2; these years exhibited relatively low and high flows, respectively. This figure presents sigma density, which corresponds to the difference between the total water density (calculated as a function of salinity and temperature) and the value 1,000 kg/m^3. The model captures the timing and extent of stratification downstream of Onondaga Lake in 1997, as well as its absence in 2000.

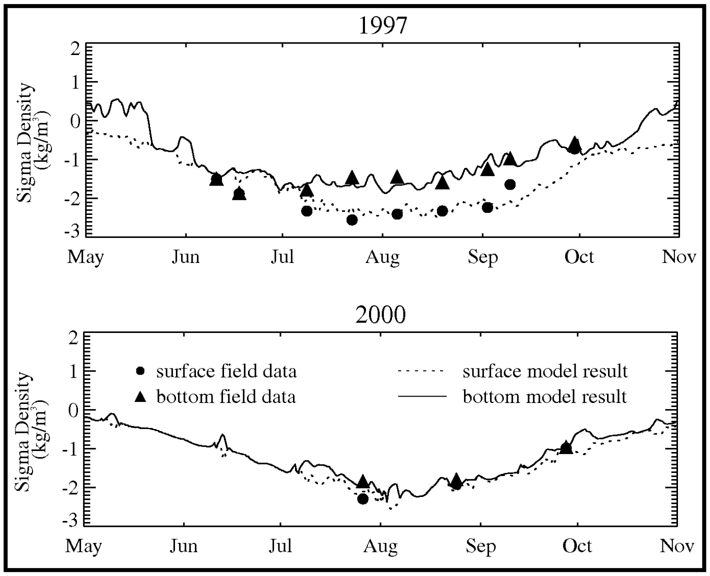

Figure ES-2. Comparison of model predicted and observed stratification at Buoy 255 located downstream of Onondaga Lake during a low flow (1997) and high flow year (2000).

ES.3.2 Water Quality, Zebra Mussels, and Sediments

Calibration of the water quality model focused on visually optimizing the model’s ability to simulate dissolved oxygen, chlorophyll-a, ammonia, nitrite, nitrate, soluble reactive phosphorus (SRP), and zebra mussel growth. Water column kinetics, sediment fluxes, and zebra mussel growth were calibrated simultaneously. The model was initially calibrated using water quality data collected in 1999, when the zebra mussel survey was performed. Calibration to the 1994-1998 and 2000 datasets was accomplished by adjusting total zebra mussel density in the river while honoring mussel cohort fidelity and the relative densities observed in the 1999 data. The value of integrating the calibration of the water quality and zebra mussel models is that the calibration of the water quality variables constrains the zebra mussel model, and likewise the requirement to honor tissue stoichiometry and the observed zebra mussel growth constrains their impacts on carbon, nitrogen, phosphorus, and oxygen levels in the water column.

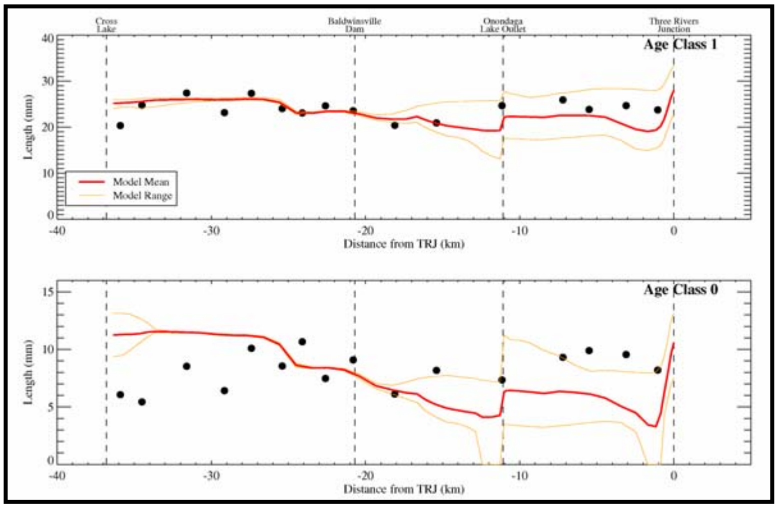

Figure ES-3. Average lengths of mussels at the end of the 1999 growing season throughout the Seneca River. Lines represent the range in model results for the 10 vertical layers modeled. Symbols represent averages of the November 1999 survey by Beak (2000b).

The computed and observed lengths of age 0+ and age 1+ mussels at the end of the 1999 growing season are presented in Figure ES-3. From just downstream of Cross Lake to the Onondaga Lake outlet (km -15), age 1+ mussels grew from approximately 8 mm (i.e., the size of the age 0+ mussels at the end of the growing season) to between approximately 20 and 27 mm in both the model and data (Figure ES-3). In this region, computed growth was similar at all depths. Downstream of the Onondaga Lake outlet, the size data are within the range of computed sizes, although the average lengths computed by the model were about 2 to 3 mm less than the average of the data. Computed growth in this region of the river varied considerably with depth due to the complex dynamics, including elevated phytoplankton growth at the surface and the plunging inflow of dense algae-rich lake water, extensive mussel filtration and respiration, and limited vertical mixing. Measured average sizes of age 0+ mussels downstream of Onondaga Lake ranged from 5 to 11 mm (Figure ES-3), similar to the range of measured sizes (3 to 12 mm). However, the quality of the fit on a location-by-location basis was not as good as for the age 1+. This is because there were additional sources of uncertainty for age 0+ mussels, including their size at settling and the date(s) of settlement.

The model captures the trends in average dissolved oxygen levels throughout the Seneca River (Figure ES-4), including the two critical regions of historical oxygen minima, Baldwinsville (Buoy 316 at km 21) and the reach between Buoys 269 and 222 (km 9 to 3). The model also captures the gradients in the other key parameters: chlorophyll-a decreases and nutrients increase downstream of Cross Lake (km -37 to -11); and chlorophyll-a and nitrogen species increase at the confluence with Onondaga Lake (at km -11). The model overestimates the increase in chlorophyll-a downstream of Onondaga Lake, a region in which complex physical and biological interactions between the chlorophyll-rich waters of the lake, the chlorophyll-poor waters of the river, and hypersaline groundwater complicate model-data comparisons.

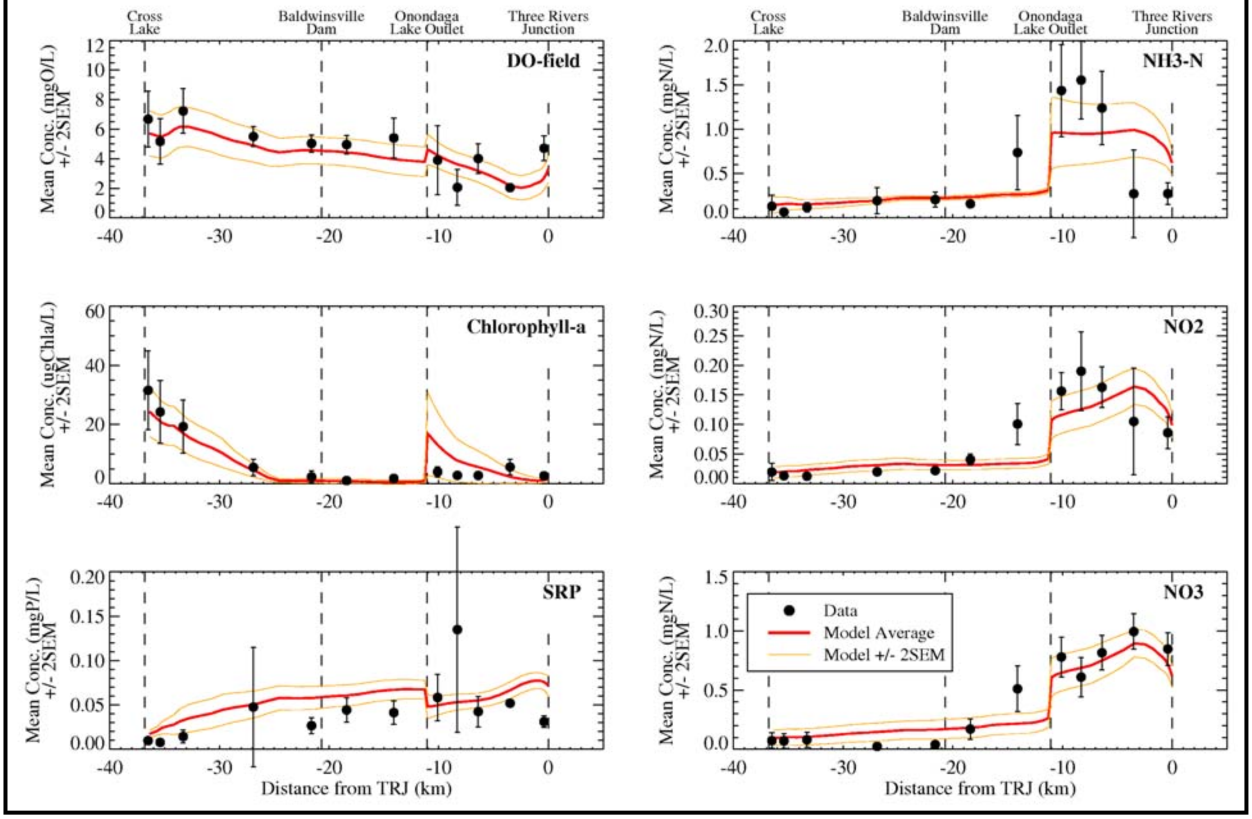

Figure ES-4. Comparison of model predicted and observed spatial profiles of Seneca River dissolved oxygen (DO-field), Chlorophyll-a, soluble reactive phosphorus (SRP), ammonia (NH3-N), nitrite (NO2), and nitrate (NO3). Data and model represent mean +/- 2 standard errors of the mean (SEM) for bottom waters (1 m above sediment/water interface) during 14 surveys conducted between 1994 and 2000 with flows less than 700 cfs.

Point-by-point comparison of time trends indicate that both the model and data show a general pattern of decline in DO in the bottom waters at Buoy 316 during the growing season, followed by a rise during the fall (Figure ES-5). The model captures the year-to-year differences with greater declines observed in 1995 and 1998 compared to those in 1997 and 2000. Comparisons between the statistical distributions of observed and computed dissolved oxygen levels within the bottom waters at Buoys 316 and 255 under moderately low-flow conditions (less than 1500 cfs) indicate no significant statistical differences ($p<0.05$) based upon Kolmogorov-Smirnov tests (Figure ES-6; Miller et al. 1990). Moreover, the computed and observed frequencies of state water quality standard violations are not significantly different based on the McNemar's Exact test (Rosner 2000). Such statistical comparisons of model and data in terms of regulatory compliance frequency provide a robust test of the model's utility for water quality management.

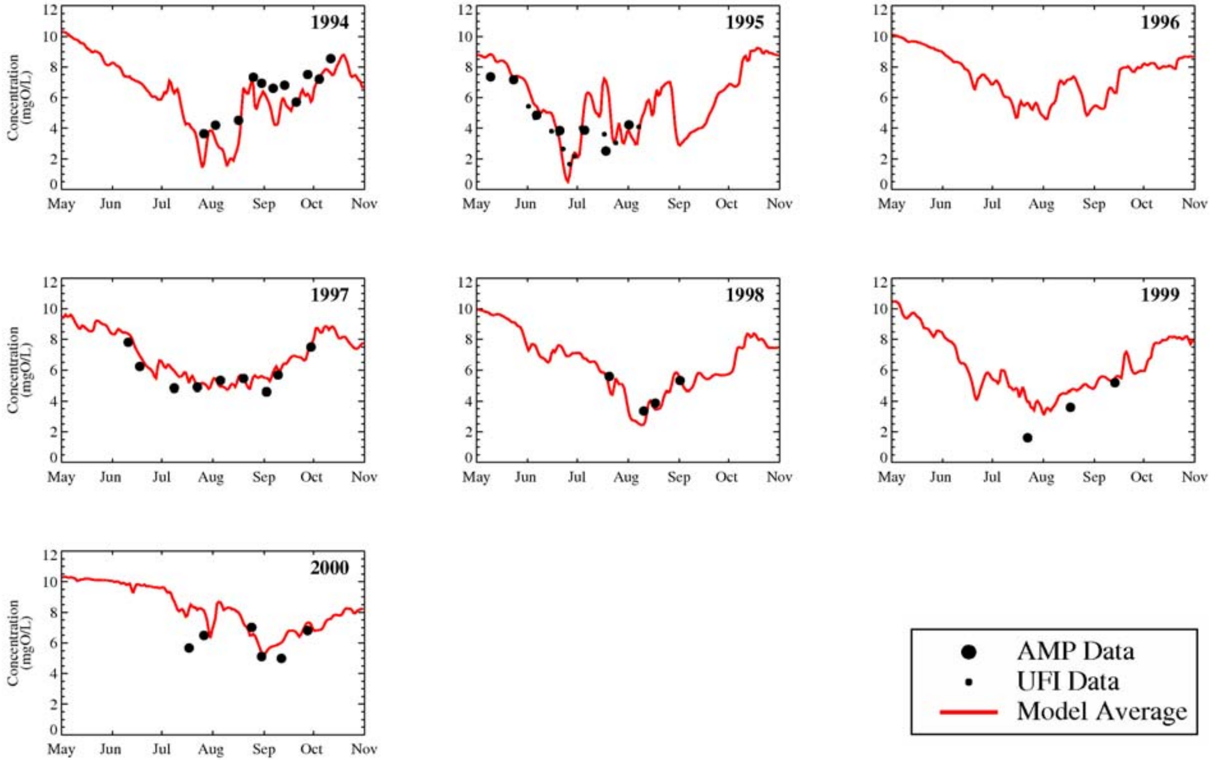

Figure ES-5. Comparison of model predicted and observed temporal profiles of Seneca River dissolved oxygen within the bottom waters (1 m above the sediment/water interface) at Buoy 316 near Baldwinsville, N.Y.

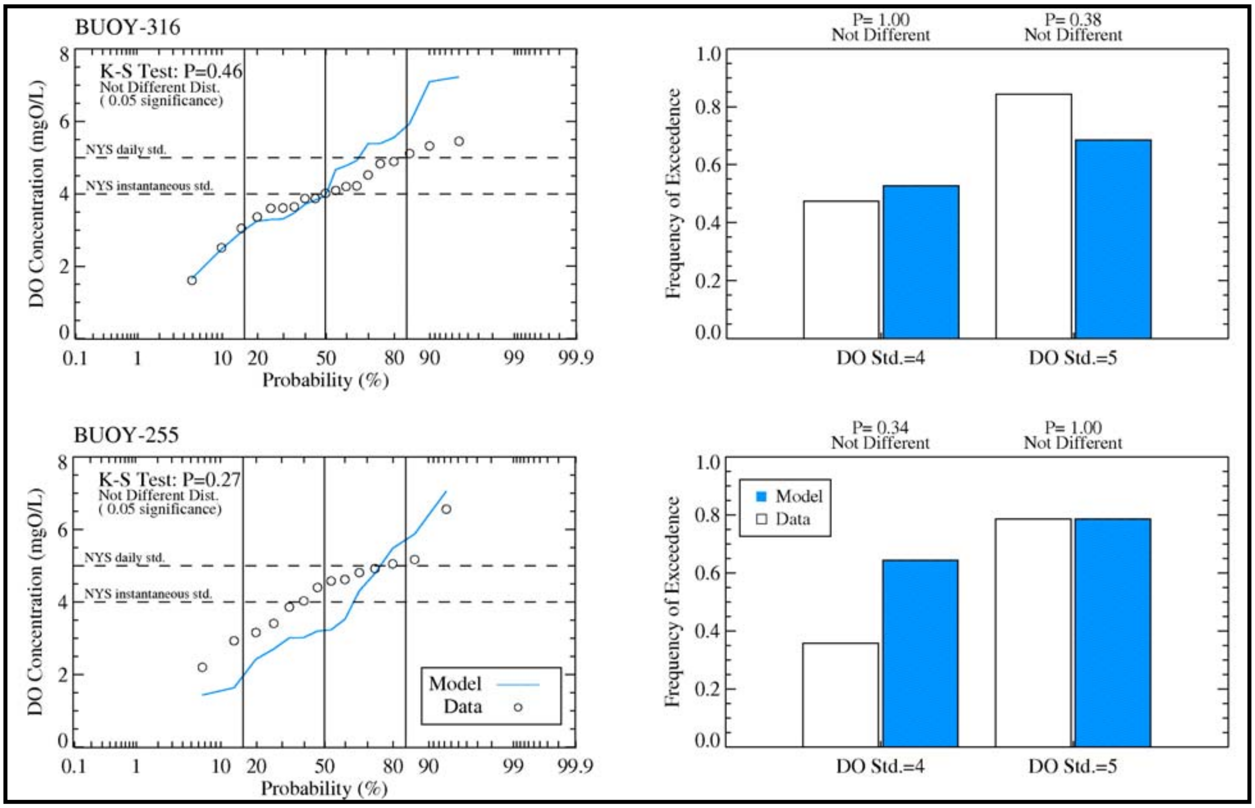

Figure ES-6. Comparison of model predicted and observed probability distributions of dissolved oxygen at Buoy 316 and 255 during July and August 1994-2000 under flows less than 1500 cfs and associated frequency of exceedances of New York State's criteria.

ES.4 INTEGRATION INTO UNIFIED WATERSHED, LAKE, AND RIVER MODELING FRAMEWORK

This report documents the development of a mechanistic model for the Three Rivers System. The OLP and USGS are developing a model of the Onondaga Lake watershed. Onondaga County and the OLP have initiated the development of a water quality model of Onondaga Lake to effectively link the watershed model with the Three Rivers model and complete a water quality management tool for the system. Together, these models will facilitate: 1) an integrated understanding of the response of Onondaga Lake and the Seneca River to potential future changes in source loadings; and 2) the effective management of water quality within the system.