Status Report 1 Outfall Redesign Study

SPDES Number NY0244741

Cornell University
Department of Energy & Sustainability

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Executive Summary

This status report presents the work accomplished between May and December 2014 related to the preliminary redesign of the outfall of Cornell University's Lake Source Cooling (LSC) system, a project required by the permit issued by New York State Department of Environmental Conservation (NYSDEC) to Cornell for continued operation of the LSC facility on Cayuga Lake. NYSDEC is planning to develop a phosphorus Total Maximum Daily Load (TMDL) allocation for the southern shelf of Cayuga Lake; this regulatory segment is classified as impaired. Development of a water quality model of Cayuga Lake that will serve as the technical foundation for the TMDL allocation is underway. The water quality model may be applied to evaluate whether limiting the phosphorus transferred from deeper in Cayuga Lake to the southern basin through the LSC facility's outfall would have any discernable impact on water quality conditions. NYSDEC has required Cornell to complete a preliminary redesign study of the LSC facility outfall, in the event that a future TMDL phosphorus allocation would make relocation of the outfall a practical and cost-effective approach to compliance.

As written in the facility's SPDES permit:

> "The requirement of this Study shall be to evaluate the current mixing zone of the discharge, identify one or more discharge locations in waters of sufficient depth to ensure that the discharge plume remains below the photic zone and to determine that the discharge will not contribute to an impairment of the designated uses of the Lake."

A workplan for the outfall redesign study was submitted to NYSDEC in early 2014, and approved on May 1, 2014. In this first status report we discuss progress with evaluating the current hydrodynamic conditions on the southern shelf and its exchange with the main body of the lake, calculating photic zone depth, and identifying an alternative discharge location outside of the impaired region of the lake that meets the criteria.

Alexandra King and Edwin Cowen of Cornell's DeFrees Hydraulics Laboratory have made substantial progress with setting up and testing a three-dimensional hydrodynamic model of the southern shelf of Cayuga Lake. The model, Si3D, has been applied to evaluate current conditions of mixing and water residence time on the shelf under various conditions of stream flow and winds. The existing LSC outfall diffuser has been analyzed using the mixing zone model CORMIX 2 to characterize near-field mixing dynamics and enable Dr. King and Dr. Cowen to modify the Si3D framework to accommodate the near-field mixing. Their initial results indicate that wind-driven circulation is the primary mechanism flushing the southern shelf. Stratification, via internal waves, strongly enhances the effect of wind on flushing. In cases where internal wave activity is low and the water on the shelf is flushed primarily by the tributaries, the LSC outfall appears to strongly reduce the shelf residence time. These results are preliminary, but provide insight for further investigation.

The alternative outfall location is to be sited in the Class AA region of Cayuga Lake and deep enough that the return flow from the LSC facility remains below the photic zone. The workplan submitted to DEC states that "The critical photic zone depth will be defined as the upper 75% of the 1% PAR depth

measured at LSC site 6 (June 1-Sept. 30, all years)". 1% PAR depth is the depth to which 1% of ambient light penetrates into the water column, and site 6 is located just north of the 303d line. DEC approved the submitted workplan with one additional requirement: that May and October be considered as well. By the approved workplan definition, the photic zone depth is calculated from 10 years of optical data at 13.55 m over the summer (June –September) and 14.9 m when May and October are included.

To screen for possible locations for a relocated outfall that would keep the return flow below this critical depth, Dr. King and Dr. Cowen set up a CORMIX 1 model. This analysis predicts the depth in the water column to which the LSC return flow would rise, under a series of assumptions representing three worst-case scenarios (i.e., scenarios resulting in the highest rise of the plume). The worst-case scenarios were defined using historically observed and design operating parameters of the LSC system in conjunction with the most unfavorable ambient (meteorological) conditions that are theoretically possible at the discharge site (unstratified water column at 4°C, zero ambient current, zero wind). Using the worst possible meteorological conditions obviates the need to consider a range of meteorological conditions. Three alternative discharge locations that keep the mixing zone of the LSC return flow below the photic zone and within the Class AA segment have been identified based on this CORMIX 1 analysis. Additional analysis was completed using CORMIX 1 to identify alternative discharge sites that would meet the criteria in May and October. By this method of analysis, the appropriate location would be determined entirely by projected operating conditions of the LSC system.

Applying the 3D model Si3D to project the mixing of a relocated LSC outfall would enable the project team to evaluate more realistic ambient conditions. We have concluded that application of the 3D model would only lead to more favorable predictions of the mixing zone location, since ambient stratification arrests the rise of the plume, and ambient current and wind increase dilution rate. Hence, it is not necessary to involve the 3D model in the evaluation of an alternative discharge location unless Cornell's Energy & Sustainability leadership determines that cost or other factors make it advantageous to complete a more precise analysis. The location recommended by a CORMIX I analysis of a worst-case design scenario is appropriately conservative for the preliminary design plan.

Project work will continue over the next eight-month reporting period. Upcoming tasks include continuing the set-up and validation of the Si3D model of the existing outfall. Once validated, the model will document the effective transfer of water between the southern shelf and the main body of the lake and support calculations of the residence time of water on the shelf, with and without the LSC outfall. We plan to select an engineering consultant to assist Cornell with the preliminary design and permitting requirements for an outfall redesign. The project is on schedule for submittal of the final approvable report on or before November 1, 2016.

1. Introduction

Cornell University's Lake Source Cooling (LSC) facility supplies chilled water to air condition and dehumidify buildings on the university's Ithaca campus, and cool research equipment and spaces. The LSC process uses the renewable resource, naturally cold water deep in Cayuga Lake, in a non-polluting heat exchange process. This process draws water from deep in Cayuga Lake, where temperatures remain cold year-round, and circulates lake water through a heat exchange facility, located on East Shore Drive in Ithaca. The lake water transfers its chill to a second closed loop of water that is connected to the campus cooling system. Slightly warmed water is returned to southern Cayuga Lake through an underwater diffuser. The lake water and campus chilled waters never mix.

A State Pollutant Discharge Elimination System (SPDES) permit has been in place for the LSC facility since March 1998. The facility came on line in July 2000. The SPDES permit was renewed, effective May 1, 2013, with several modifications and new conditions. This status report summarizes work accomplished to date on one of the permit requirements: to complete a preliminary redesign study for a modified outfall of the LSC facility. These modifications to the outfall would be implemented in the event that Cornell determines that they would represent the most practical and cost-effective approach to prevent against a potential water quality impairment or to comply with a future phosphorus limit.

The language from the SPDES permit requiring the LSC outfall redesign study is cited below.

"In compliance with Title 8 of Article 17 of the Environmental Conservation Law of New York State and in compliance with the Clean Water Act, as amended, (33 U.S.C. 1251 et. Seq.), per SPDES Permit Number NY 0244741 (http://www.dec.ny.gov/docs/water_pdf/cornelllscprmt.pdf), effective May 1, 2013, Cornell (permittee) shall comply with the following schedule for permit compliance:

> *"The permittee shall develop and submit an approvable plan for an Outfall Redesign Study to evaluate potential alternative sites for relocating the discharge from Outfall 001 to a location within the Class AA segment of Cayuga Lake (as depicted by transect A-A' on the Monitoring Locations map and defined in 6 NYCRR Part 898.4, Table I, Item 227).*
>
> *"The requirement of this Study shall be to evaluate the current mixing zone of the discharge, identify one or more discharge locations in waters of sufficient depth to ensure that the discharge plume remains below the photic zone and to determine that the discharge will not contribute to an impairment of the designated uses of the Lake."*

The Cornell project team developed a draft workplan for completion of the required outfall redesign study, and met with NYSDEC staff in Albany NY in December 2013 to discuss the technical elements of the planned approach. We modified the draft workplan in response to discussion during the December meeting; a final version of the workplan was submitted to NYSDEC in January 2014. The workplan was approved, with one additional requirement, on May 1, 2014; this effective date of workplan approval

(EDA) defines the schedule set forth in the May 1, 2013 SPDES permit for the required status reports and final report of the outfall redesign study.

The permittee shall submit Outfall Redesign Study status reports:

	EDA + 8 months	(Jan 1, 2015)
	EDA + 16 months	(Sept 1, 2015)
	EDA + 24 months	(May 1, 2016)
The permittee shall submit an approvable final report:	EDA + 30 months	(Nov. 1, 2016)

2. Summary of Progress by Workplan Task

The approved workplan includes a table of objectives and tasks that will enable Cornell to meet the requirements of the SPDES permit condition related to the outfall redesign study. The objectives and tasks are summarized in Table 2-1 along with a brief status update as of EDA + 8 months. The additional task requested by NYSDEC as part of the workplan approval is designated in blue text.

Table 2-1. Summary of progress with workplan tasks

Objective	Task	Status Update EDA+ 8 months
Evaluate current mixing zone of the LSC return flow	Complete a three-dimensional (3D) model of the LSC return flow under current conditions: flow rate and temperature of LSC return flow; meteorological forcing functions; diffuser configuration; flow rates from IAWWTP and VCHWWTP.	Alexandra King and Edwin Cowen have made substantial progress with setting up and testing a three-dimensional hydrodynamic model of the southern shelf of Cayuga Lake, (Si3D). Current conditions of mixing and water residence time on the shelf have been analyzed under various conditions of stream flow and wind conditions. The existing LSC outfall diffuser has been analyzed using CORMIX to characterize the near-field mixing dynamics and enable the researchers to modify the Si3D framework to accommodate the near-field mixing. **(section 3)**
	Validate the 3D model using data from the RUSS, thermistor at the pile cluster, LSC intake temperature records, and other measurements specifically for this study.	
	Use the validated model to simulate the 3D velocity and temperature fields under current conditions, from which estimates of the spatio-temporal evolution of the LSC outfall plume will be determined.	
	Quantify the effects of the LSC return flow on residence time of Cayuga Lake water on the shelf.	
Identify an alternative discharge location that meets criteria	Define the depth of photic zone in Cayuga Lake, based on statistical analysis of light profile data in Class AA segment collected 1999-2006, 2013.	Data from UFI ambient monitoring of Cayuga Lake optical properties (1998-2006; 2013) have been analyzed to define the depth of the photic zone. **(section 4)**
	Apply model to a new outfall located within the Class AA segment of Cayuga Lake in order to project the configuration of the discharge plume of LSC return flow during the critical period for phytoplankton growth (June 1-Sept 30).	Several alternative discharge locations that meet the criteria (keeping the mixing zone of the LSC return flow below the photic zone and within the Class AA segment) have been identified based on CORMIX analysis of three worst-case design scenarios

	Discuss the potential impact of return LSC flow through a new outfall during May and October (per NYSDEC request 5/1/14) Investigate potential effects of a range of meteorological conditions on projected plume from relocated outfall.	that are motivated by historical and theoretical operating parameters of the LSC system. These worst-case scenarios represent the most unfavorable meteorological conditions that can possibly occur, so they are extremely conservative, obviating the need to consider a range of meteorological conditions. Additional analysis was conducted to identify alternative discharge sites that would meet the criteria in May and October. **(section 5 and Appendix A)**
Compare environmental impacts of existing and alternative outfall	Apply the hydrodynamic and eutrophication models to project summer phosphorus and chlorophyll concentrations in 303(d) listed (Class A, southern shelf) segment and main lake (Class AA segment) of Cayuga Lake, under two scenarios: current outfall and redesigned outfall.	0% complete (pending completion of the eutrophication model)
Develop alternative outfall	Complete conceptual design of outfall extension/relocation	0% complete
	Develop (engineers opinion of) costs for permitting, design, survey, bidding, construction	0% complete
Prepare detailed implementation schedule	Identify potential suppliers and contractors; develop critical path timeline for acquisition of pipe and other materials.	0 % complete
	Identify required regulatory permits and approvals from NYSDEC, ACOE, and any local municipalities; including SEQRA compliance	0% complete
	Identify required easements from OGS	0% complete
Submit outfall redesign study to NYSDEC	Report to comply with SPDES special condition	0 % complete (due EDP+30 months, 11/1/2016)

3. Status of the Hydrodynamic Model of the Current LSC Outfall

In this section we review our progress in developing the three-dimensional hydrodynamic model that will be used to evaluate the current mixing zone and residence time of the LSC return flow on the southern shelf. The numerical model, Si3D, to which we have added a near-field mixing model for the Lake Source Cooling (LSC) outfall plume, solves the Reynolds-averaged Navier-Stokes, continuity, and scalar transport equations on a Cartesian grid, employing the hydrostatic assumption for pressure and the eddy viscosity formulation for Reynolds stress (Smith, 1997; Rueda, 2001). Model boundary conditions include surface heat flux and wind stress, tributary flow rates and temperatures, and point source flow rates and temperatures. Passive tracer releases of arbitrary initial distribution may be used to quantify residence time within a given region at a given release time. We are using, at minimum, measurements from 2012, 2013, and 2014 to calibrate and validate the model.

Here we describe development of the numerical mesh and review the field data that will be used to define model boundary conditions and initial conditions and to calibrate and validate the model. We also classify the current LSC outfall plume according to the CORMIX II framework and describe our modification of Si3D to incorporate the appropriate near-field mixing model based on this framework. Finally, we review results of some preliminary model validation studies and show some results of preliminary studies of the LSC outfall's impact on shelf-wide residence time.

3.1 Numerical Mesh

The numerical mesh was developed for the three-dimensional model from the following sources of bathymetric data:

1. Cayuga and Seneca Lakes NOAA Canal System chart 14791 (paper, pre-1974)
2. Lake Source Cooling as-built survey (1996)
3. NYS Canal Corporation soundings (2006 & 2008)
4. Cornell soundings on shelf (Vandebroek, 2011)
5. Cornell shoreline survey (Vandebroek, 2011)

Horizontal coordinates of these data points are plotted in Figure 3-1. Depth measurements were interpolated onto a Cartesian grid using the natural neighbor method (e.g., Vandebroek, 2011). For the model mesh, Cayuga Lake was rotated 26° clockwise within the horizontal plane so the LSC discharge direction aligns with cell boundaries – this minimizes numerical diffusion error. Tributaries were included in the mesh up to the location of the first hydraulic jump upstream of the lake, identified in a field survey. Above this first hydraulic jump, flow is supercritical, meaning surface waves cannot propagate upstream.

In order to resolve the near field plume region of the point sources on the southern shelf region of Cayuga Lake, we require a finer mesh for this region than is computationally feasible for the entire lake. Hence, our final model runs will employ two consecutive simulations with different meshes. First we will run a coarse mesh simulation for the entire lake, and then we will use the solution from that

simulation to specify the northern boundary condition for a second simulation employing a finer mesh for the southern basin only. We are currently testing a 125m x 125m grid for the entire lake (coarse grid) and both a 25m x 25m and a 5m x 5m grid for the southern basin (finer grid). The 125m x 125m and 5m x 5m meshes are plotted in Figure 3-2. Note that tributaries are rotated to align with the cell boundaries (to reduce numerical diffusion error and, in the case of the 125m x 125m mesh, to obtain connectivity) but for the southern basin mesh the tributary angle at the mouth is preserved in order to correctly model momentum input from the streams to the shelf. Cell height is uniform in the horizontal plane and the same for both meshes, at present varying from 0.5m at the lake surface to several meters at the lake bottom in the main lake basin. Run time and memory usage for a typical one-month simulation using a computer with a 2x 3.06GHz 6-Core Intel Xeon processor and six 8Gb memory cards are given in Table 3-1 for the different meshes. The final grid resolution for the coarse and fine grids will be chosen to balance computational resources and predictive capability. At this time we are working with a 125m x 125m coarse grid and a 25m x 25m fine grid.

Table 3-1. Si3D memory usage and run times for simulations employing different domains and mesh resolutions

Mesh domain	Mesh resolution	Memory usage	Run time for one-month simulation
Entire basin	125m x 125m	200 Mb	5 hours
Entire basin	25m x 25 m	5 Gb	1 month
Shelf only	25m x 25 m	500 Mb	54 hours
Shelf only	5m x 5m	5 Gb	4 months

Based on a computer with a 2x 3.06GHz 6-Core Intel Xeon processor and six 8Gb memory cards.

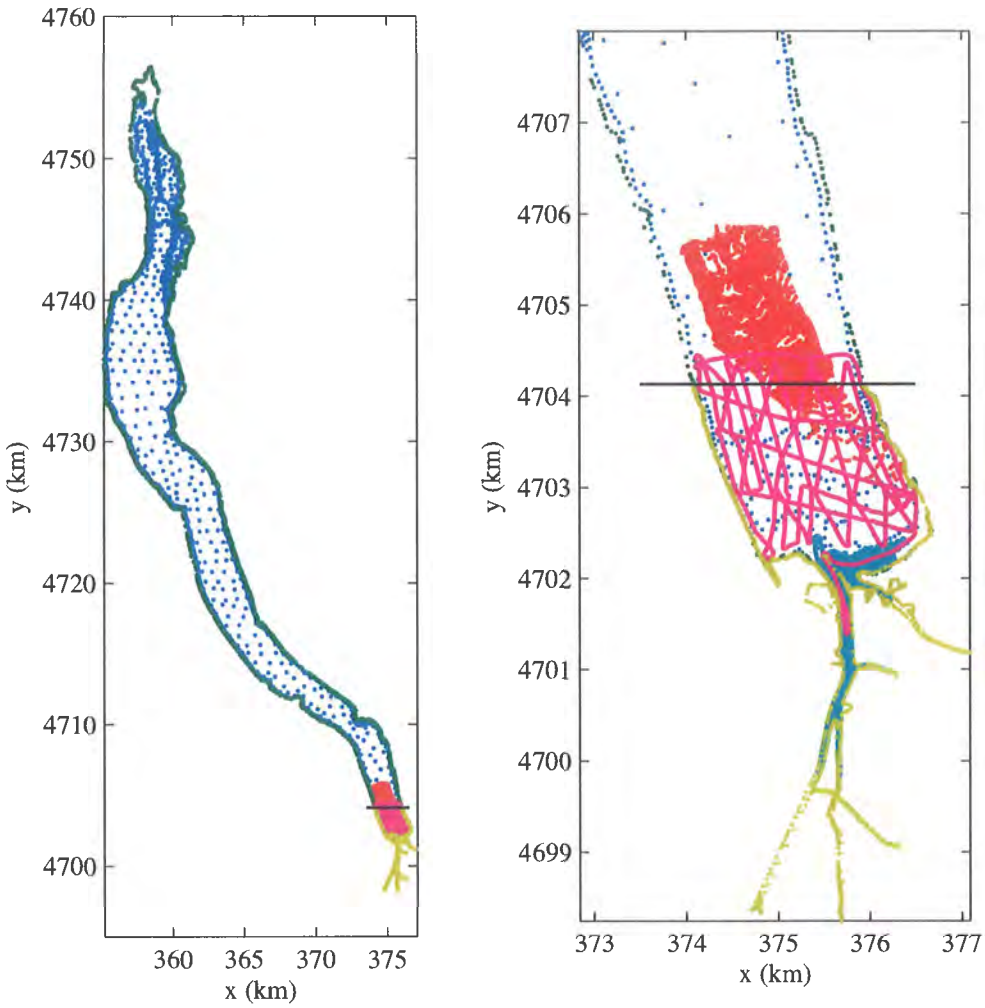

Figure 3-1. Coordinates (UTM Zone 18T) where depth and shoreline measurements are available.

Source of data is indicated by color: Blue = depth from NOAA chart, Green = shoreline point from NOAA chart, Red = depth measurement from LSC as-built survey, Cyan = depth measurement from NYS Canal Corporation, Magenta = Cornell depth measurement, Gold = Cornell shoreline measurement. Black line = 303(d) line.

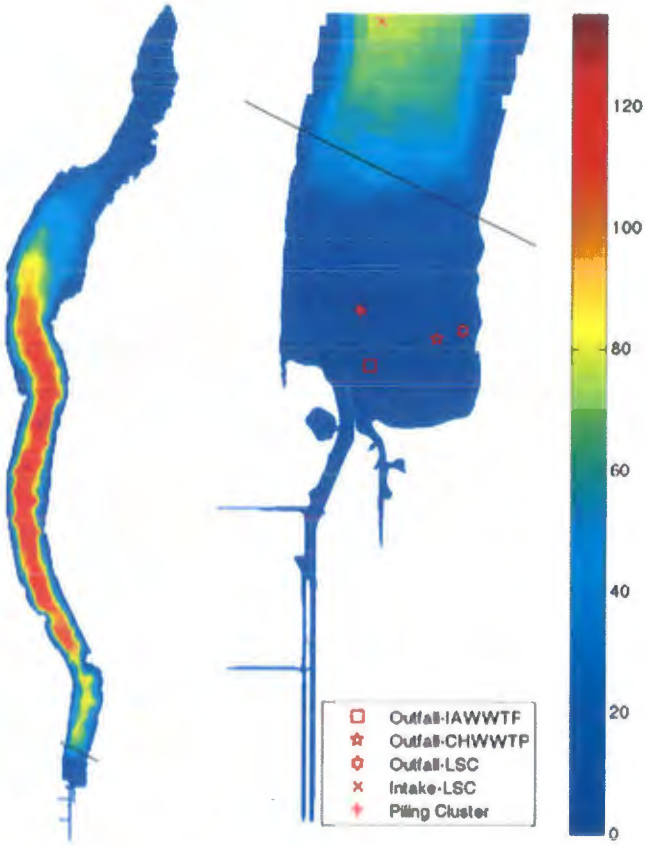

Figure 3-2. Bathymetric maps used as input for Si3D. 125m x 125m grid for entire lake on left, 5m x 5m grid for shelf only on right. Locations of point sources, LSC intake, and piling cluster are shown on shelf. Color indicates meters below mean summer lake level. For each grid, 303(d) line is plotted in black.

3.2 Supporting Field Data

3.2.1 Temperature Measurements

Thermistor strings have been deployed by Cornell University for research purposes between 1998 and present. From year-to-year, deployment times and locations have varied; thermistor strings were typically deployed in summer and fall in deep water with thermistors spaced several meters apart to resolve the thermocline, recording measurements every 1-2 minutes. In 2012, 2013, and 2014, thermistor strings were deployed near the LSC intake in ~80m of water.

Continuous water temperature records are also available from single thermistors at the piling cluster and from the LSC intake water. Locations of the piling cluster and the intake are shown in Figure 3-2. Intake water temperature is measured at the HXF. Piling cluster measurements date back to 1998 and hourly intake temperature measurements began in 2005.

These temperature records will be used to calibrate and validate Si3D. Thermistor string records are

also used to generate the initial condition. Si3D is initialized with zero velocity everywhere and temperature specified as a function of depth alone. It requires some care to obtain a temperature profile that is representative of the entire lake from a vertical profile measured at a single spatial location subject to internal wave activity (i.e., the thermistor string location). The internal wave period depends on stratification conditions and is typically around 2.5 days in mid-summer. To obtain a lake-wide temperature profile from the thermistor string data, we first average the profile over a short time scale (e.g. 15 minutes) to smooth oscillations due to small waves and turbulence. Then we locate the thermocline, defined as the location of maximum temperature gradient, as a function of time. We re-center the profile at the thermocline and then take a moving time-average of temperature at each height (relative to the thermocline) over several days to average over the internal waves. We also take a moving time-average of thermocline depth and add the averaged thermocline depth back to the depth axis. Finally, we obtain the initial condition for lake temperature from the averaged time history of the temperature profile at the appropriate time. This method allows us to average over internal waves while maintaining the correct temperature gradient at the thermocline.

3.2.2 Meteorological Measurements

Meteorological measurements (wind velocity, air temperature, shortwave radiation, and relative humidity) were made every 10 minutes at the piling cluster (location shown in Figure 3-2) from October 2011 through present. Prior to October 2011, meteorological measurements are available from a land-based station operated by Cornell at Game Farm Road and from another station at the Ithaca Airport. Wind measurements differ somewhat between the piling cluster and Game Farm Road stations. Gelda et al. (2014) found that using on-lake meteorological measurements (from the piling cluster) to drive their two-dimensional Cayuga Lake simulations for 2012 and 2013 produced significantly better results than using Game Farm Road meteorological measurements. They developed a least square linear transform method to predict wind velocities at the piling cluster based on wind velocity measurements at the Game Farm Road station and found the transformed Game Farm Road wind velocities produced better model results than the untransformed velocities. Consequently, we will use piling cluster meteorological measurements when available and transformed land-based measurements if periods previous to October 2011 are modeled or if piling cluster measurements are not available during short periods. Along with piling cluster measurements of water temperature and Upstate Freshwater Institute's measurements of light attenuation, these meteorological measurements provide surface boundary conditions for Si3D: surface heating and cooling for the temperature transport equation and surface wind stress for the momentum transport equations.

3.2.3 Lake Water Level Measurements

Lake water level is measured every 15 minutes by the USGS in Cayuga Inlet (Station 04233500). Water level is specified as the northern boundary condition for the basin-wide mesh and is also used to validate simulations. Even during persistent strong wind events, the difference in water surface elevation between Cayuga Inlet and the northernmost end of the lake rarely exceeds 10cm, so the water surface elevation measured at Cayuga Inlet is a reasonable representation of water surface elevation across the entire lake. Specifying the water surface elevation as a model boundary condition ensures the

correct mass balance over longer time-scale variations in water surface elevation that are controlled at the lake outlet at the north end.

3.2.4 Tributary Inflow Measurements

Tributary flow rates are measured every 15 minutes by the USGS at Fall Creek, Six Mile Creek, and Cayuga Inlet. Gage station numbers and watershed areas are summarized in Table 3-2. Total watershed areas are from Haith et al. (2012). The area weighting method is used to convert measured flow rate to flow rate entering Cayuga Lake. Flow rate in Cascadilla Creek, which is not gaged, is estimated from Six Mile Creek flow rate measurements using the area weighting method. Boundary conditions for stream inputs include flow rate and stream temperature; some stream temperature measurements are available, and stream temperature is set to a moving average of air temperature where other measurements are not available.

Table 3-2. Gage station numbers and watershed areas for southern shelf tributaries

Tributary	USGS Gage Number	Watershed Area Above Gage km^2	Total Watershed Area km^2	Percent Watershed Above Gage
Fall Cr.	04234000	326.339	330.86	98.6%
Sixmile Cr.	04233300	101.010	134.11	75.3%
Cayuga Inlet	04233255	224.552	240.81	93.2%
Cascadilla Cr.	N.A.	N.A.	36.65	N.A.

3.2.5 Point Source Measurements

Temperature and flow rate of the LSC effluent has been measured hourly at the LSC Heat Exchange Facility (HXF) since 2005. Daily average flow rate and temperature records are available from the Ithaca Area Wastewater Treatment Plant (IAWWTP). Monthly average flow rate measurements (but not temperature) are available from Cayuga Heights Wastewater Treatment Plant (CHWWTP); this is the smallest of the point sources discharging to the southern shelf of Cayuga Lake.

3.2.6 Gridding Study

On August 15-16, 2014, we conducted an intensive gridding study to map the LSC outfall plume. Temperature profiles were measured at 170 points centered near the LSC outfall, and three continuous temperature records were collected at the edges of the sampling domain using thermistor strings. August 15 sampling points are plotted in Figure 3-3; sampling points were similar on August 16. During this gridding study, the U.S. Naval Research Laboratory conducted flyovers, imaging the gridded area using Sofradir ATOM LWIR, and they are processing the data to provide instantaneous maps of lake surface temperature. Temperature profiles collected during the flyovers will be used to ground truth the flyover data. If the flyover temperature data are of good quality, they will also be used to calibrate the near-field plume model within Si3D.

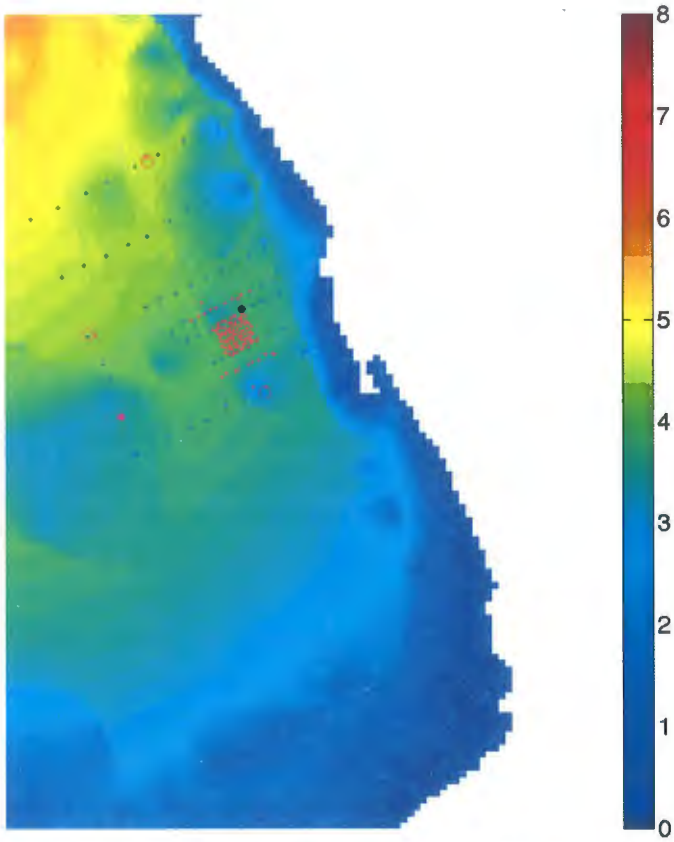

Figure 3-3. Profile locations for August 15, 2014 gridding study.

Color plot in background shows water depth (referenced to mean summer lake level) in meters. Large black dot marks location of LSC outfall, large magenta dot near the west edge of the blue dots marks location of CHWWTP outfall, small blue and red dots mark location of temperature profile measurements from two different boats, and red open circles mark locations of moored thermistor strings. Gridded region is 400m x 400m.

3.3 CORMIX II Classification of the As-Built Outfall Plume

CORMIX is a USEPA-supported mixing zone model and decision support system for environmental impact assessment of regulatory mixing zones resulting from continuous point source discharges. CORMIX II was developed specifically for assessing multiport diffusers and classifies multiport diffuser plumes using a decision tree documented in Akar and Jirka (1991). The flow class depends on the geometry of the diffuser, the effluent flow rate, the effluent density, and characteristics of the receiving water at the diffuser site. In this section we demonstrate that over 99% of the time, the LSC diffuser plume belongs to flow class MNU7 or MN2.

The as-built LSC outfall pipe extends into Cayuga Lake from the heat exchange facility on the east shore, at an angle 26° south of west (see Figure 3-4). The diffuser consists of 38 nozzles spanning the final L_D=22.8m of the outfall pipe. Diffuser ports are perpendicular to the pipe, pointing 26° west of north (fairly parallel to but slightly away from the east shore and towards the north end of the lake). The center of the diffuser section is located at UTM Zone 18T coordinate (376256mE, 4703137mN) at a depth of H=3.9m (at mean summer lake level, 116.5m above NGVD 1929). Diffuser nozzles are located h_0=0.3m above the bed and discharge at an angle θ=20.0° above horizontal. Each nozzle consists of a 6-in standard Inserta® tee. With a 0.61 area ratio for the vena contracta (appropriate at the high Reynolds numbers typical of the diffuser), total port area is A_0=0.423m^2. Temperature and volumetric flow rate of the discharge have been measured hourly at the LSC HXF from January 2005 to present. The ambient water temperature on the shelf has been measured at the piling cluster (375317mE, 4702891mN) between 1998 and present. Time series of effluent flow rate (Q_0) and temperature (T_0) are plotted along with temperature of the ambient shelf water (T_a) in Figure 3-5. The receiving water is shallow and within the epilimnion (except briefly during upwelling events, which cause significant vertical mixing), so stratification is negligible.

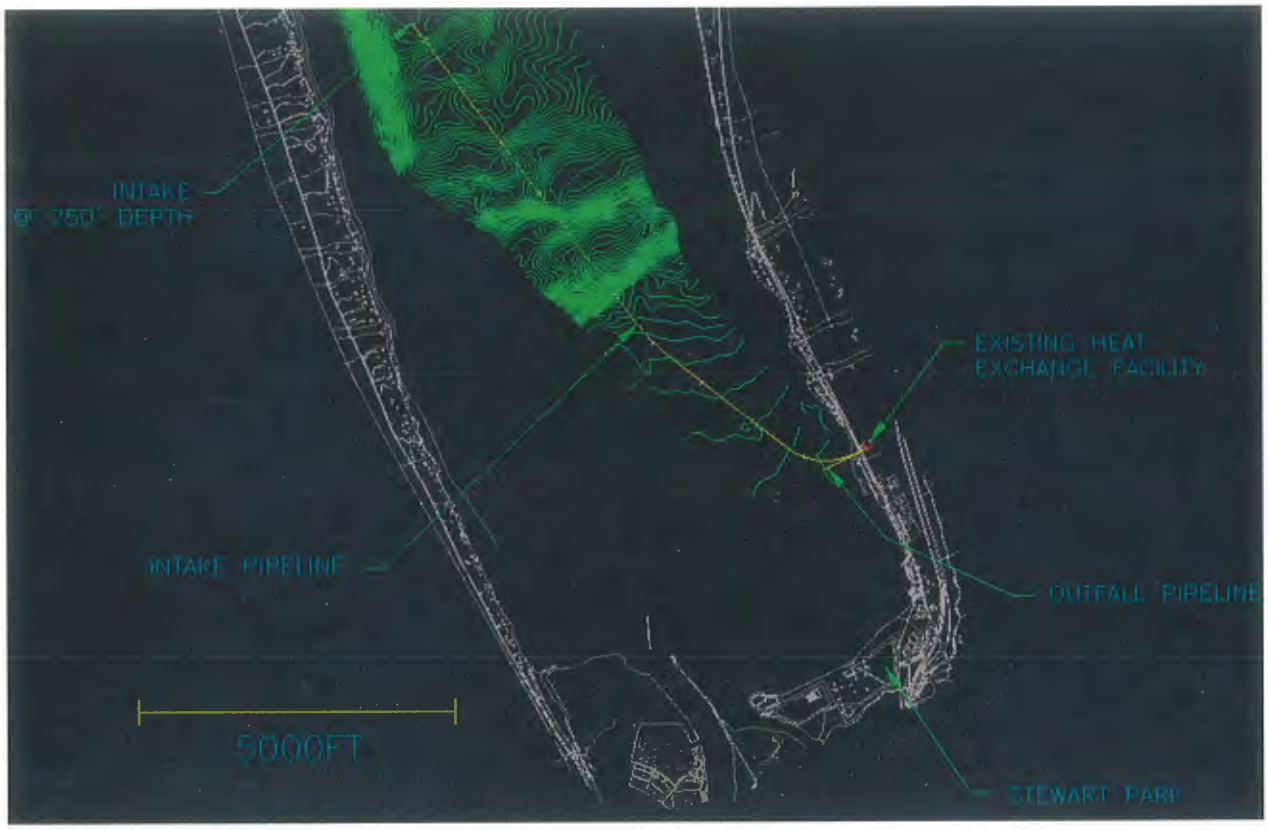

Figure 3-4. Map of LSC outfall and Intake pipelines. This is an excerpt from the as-built drawings. Green lines represent depth contours from the as-built survey.

The CORMIX II flow classification system for discharge into unstratified ambient water is based on the following two-dimensional parameters: flow rate per unit length $q_0=Q_0/L_D$, momentum flux $m_0=q_0u_0$, and buoyancy flux $j_0=q_0g_0'$ where $u_0=Q_0/A_0$ is the port velocity and $g_0' = g(\rho_0 - \rho_a)/\rho_a$ is the reduced gravity based on density of the effluent (ρ_0) and ambient (ρ_a) (Akar and Jirka 1992). Time histories of these three quantities are plotted in Figure 3-6. The LSC outfall plume is strongly negatively buoyant most of the year and weakly positively buoyant during short periods in winter. CORMIX II determines plume stability using the parameter c_7 for negatively buoyant plumes and c_4 for positively buoyant plumes:

$$c_7 = \frac{m_0}{|j_0|^{2/3}H}(1 + cos^2\theta)^2 + \frac{u_a^2}{|j_0|^{2/3}}$$

$$c_4 = \frac{m_0}{j_0^{2/3}H}(1 + cos^2\theta)^2 + \frac{u_a^2}{j_0^{2/3}} - 0.1\frac{u_a^2 h_0}{m_0}$$

where u_a is the ambient water velocity. We do not know, a priori, the ambient water velocity at the LSC discharge site, but it is reasonable to assume it is in the range of 1mm/s to 10cm/s.

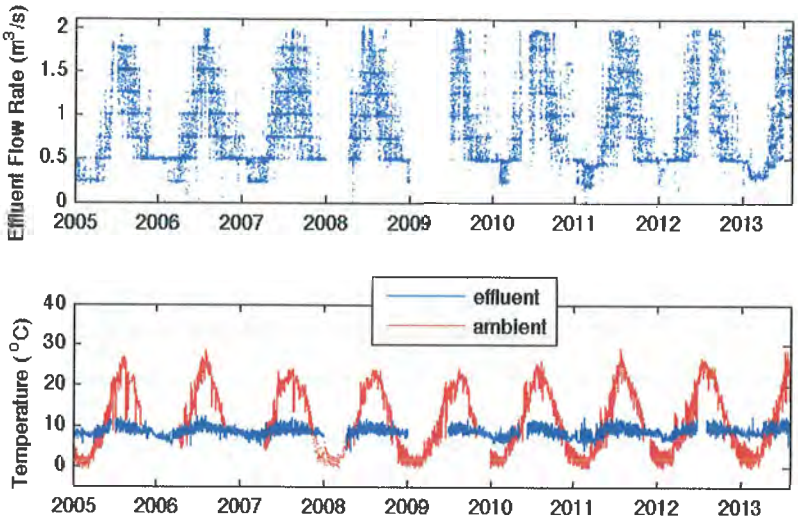

Figure 3-5. Time histories of flow rate and temperature of LSC effluent (measured hourly at the heat exchange facility) and ambient temperature of Cayuga Lake (measured at the piling cluster).

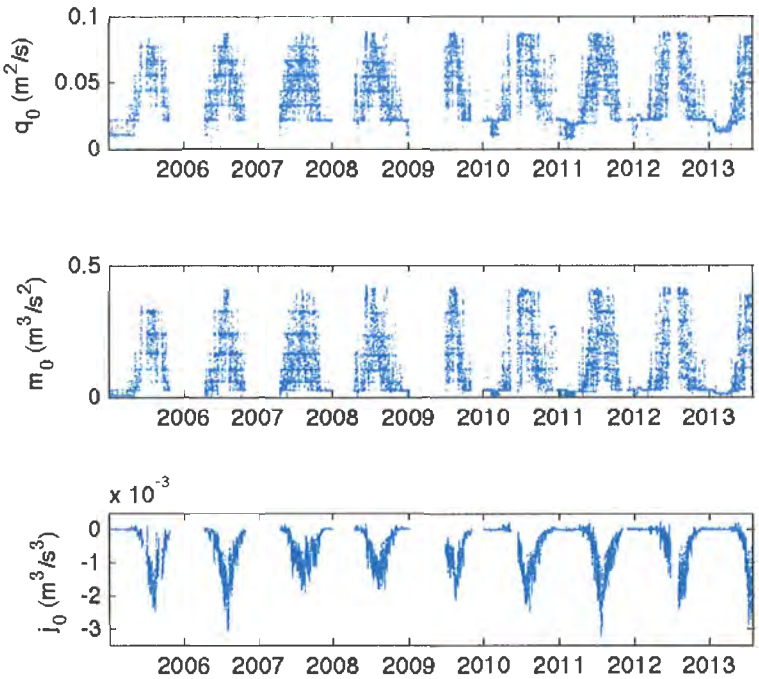

Figure 3-6. Time histories of flow rate, momentum flux, and buoyancy flux (all quantities expressed per unit diffuser length) for as-built LSC outfall.

When the stability parameter (c_7 or c_4) is smaller than 0.54, the plume is unstable in the near field, meaning its momentum is strong compared it its buoyancy, mixing the effluent uniformly over the depth of the water column. The time history of the stability parameter (c_7 when the plume is negatively buoyant and c_4 when it is positively buoyant) based on time histories of q_0, m_0, and j_a (plotted in Figure 3-6) is plotted in Figure 3-7 for ambient velocities between 0 and 1m/s. Even with zero ambient velocity, the plume is unstable greater than 99.97% of the time. Since the diffuser ports are perpendicular to the diffuser pipe, and point unidirectionally along the shore, the plume falls into CORMIX II flow class MNU7 when it is negatively buoyant and flow class MN2 when it is positively buoyant.

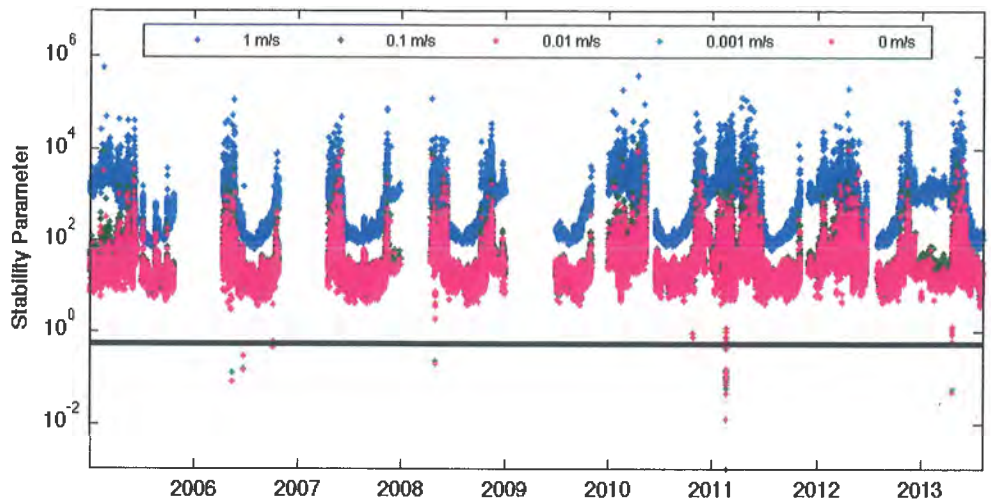

Figure 3-7. Time histories of plume stability parameter (equal to c_7 when $j_0<0$ and c_4 when $j_0>0$) for as-built LSC outfall for five different ambient water velocities (indicated in legend). Plume is stable when stability parameter drops below 0.54, which is plotted as a black line.

Flow classes MNU7 and MU2 are identical in the near field and the intermediate field (both defined below), except that if the plume stratifies in the intermediate field, it ends up below the ambient water if it is negatively buoyant (MNU7) and above the ambient water if it is positively buoyant (MU2). In Figure 3-8, we show a sketch of the plume for flow class MNU7. CORMIX II software provides the following description of the MNU7 flow class:

> "A unidirectional multiport diffuser with perpendicular alignment is discharging into an ambient flow. Frequently, this is called a 'co-flowing diffuser'. The discharge configuration is hydrodynamically 'unstable', that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). Rapid vertical mixing takes place over the full layer depth.

The following flow zones exist:

1) Acceleration zone for unidirectional coflowing diffuser: The net horizontal momentum flux provided by the diffuser jets leads to a whole scale acceleration of the ambient water, which flows across the diffuser line leading to rapid entrainment and mixing in this zone. The diffuser plume is mixed over the full layer depth, and contracts laterally in the direction of the flow (acceleration process). The length of this zone is about one half the diffuser length.

2) Diffuser-induced plume in co-flow: The diffuser-induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to spreading of the diffuser plume and additional mixing. The plume moves predominantly in the direction of the ambient flow. At the

beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy."

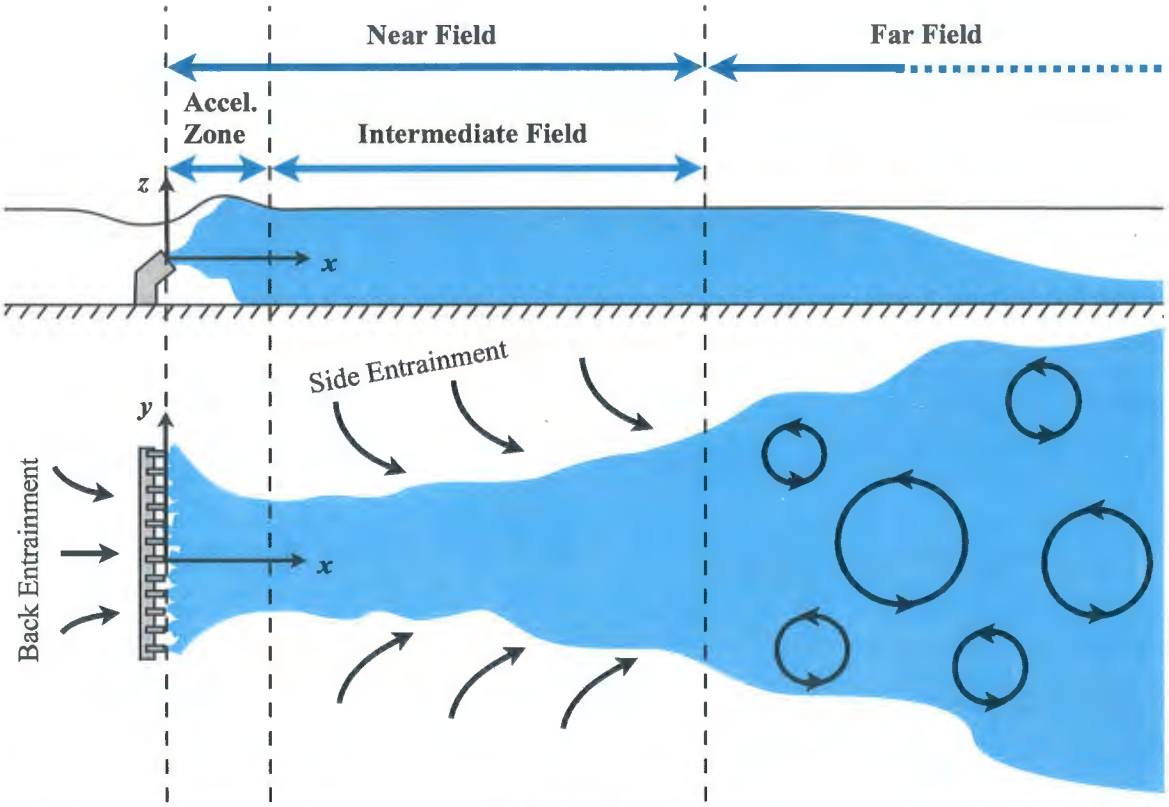

Figure 3-8. Side view and plan view sketches of the near field (consisting of the acceleration zone and the intermediate field) and the far field for hydrodynamically unstable plume discharged from a unidirectional multiport diffuser.

These zones comprise the near field and are illustrated in Figure 3-8. The first is called the "acceleration zone" and the second is called the "intermediate field". Akar and Jirka (1991) document the empirical formulas used by CORMIX II for dilution and plume half-width, and we review these formulas for the acceleration zone and the intermediate field below, neglecting ambient velocity because it is very small (maximum anticipated 0.1m/s) compared to the diffuser jet velocity (~3.5m/s). Dilution, denoted by S, is proportional to plume flow rate (the integral in y and z of the x-velocity component) and inversely proportional to plume temperature and concentration. Assuming a top-hat profile for temperature and concentration within the plume,

$$S = \frac{Q}{Q_0} = \frac{T_0 - T_a}{T - T_a} = \frac{C_0 - C_a}{C - C_a}$$

The acceleration zone spans x=0 to x=L_D/2. The plume contracts by a factor of two within the acceleration zone, starting with half-width B=L_D/2 at x=0 and ending with half-width B=L_D/4 at x=L_D/2. Dilution is constant within the acceleration zone and given by

$$S = \sqrt{\frac{m_0 H}{2q_0}}$$

The flow rate induced behind the diffuser, called "back entrainment" is equal to

$$Q_m = Q_0(S - 1)$$

where S is the dilution in the acceleration zone. For the LSC discharge, Q_m is often over twice Q_0, meaning the flow induced by the outfall is significantly larger than the flow from the outfall itself.

The intermediate field begins at $y=L_D/2$. In this region, side-entrainment is significant, so the flow rate grows downstream. Dilution grows with the square root of distance as follows:

$$S = S_{50}\sqrt{\frac{m_0 H \cos\theta_0\,(x - x_V)}{q_0^2 L_D}}$$

and the plume half-width grows linearly as

$$B = B_{50}(x - x_V)$$

where the virtual origin is located at

$$x_V = \frac{L_D}{2}\left(1 - \frac{1}{S_{50}^2}\right)$$

and S_{50}=0.58 and B_{50}=0.21 are empirical constants. Some distance downstream, either within the intermediate field or the far field, the plume may re-stratify.

3.4 Modification of 3D Numerical Model to Incorporate Point Sources and Sinks

3.4.1 Governing Equations

The governing equations within Si3D, before discretization, are presented below. Point sources are incorporated through the source strength term σ, the source velocity (u_0,v_0), the source temperature T_0, and the source passive tracer concentration C_0 following Singleton et al. (2010) (note that Singleton et al. do not include the source strength in the integrated continuity equation because it is negligible for bubble plumes, but we do include it here).

Continuity equation (conservation of mass):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \sigma$$

where t is time, (x,y,z) are the two horizontal coordinates and the vertical coordinate, respectively, and (u,v,w) are the corresponding coordinates of water velocity.

Incorporating the kinematic boundary condition for the water surface elevation into the continuity equation and integrating over the water depth:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\left[\int_{-H}^{\zeta} u dz\right] + \frac{\partial}{\partial y}\left[\int_{-H}^{\zeta} v dz\right] = \int_{-H}^{\zeta} \sigma dz$$

where the vertical coordinate, z, is zero at a reference elevation near the water surface, ζ is elevation of the water surface above that reference, and the bed is located at z = –H.

Conservation of momentum (x-component):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\left(g\frac{\partial \zeta}{\partial x} + g\frac{1}{\rho_0}\int_{z}^{\zeta}\frac{\partial \rho}{\partial x}d\xi\right) + \frac{\partial}{\partial x}\left(A_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V\frac{\partial u}{\partial z}\right) + \sigma(u - u_0)$$

Conservation of momentum (y-component):

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\left(g\frac{\partial \zeta}{\partial y} + g\frac{1}{\rho_0}\int_{z}^{\zeta}\frac{\partial \rho}{\partial y}d\xi\right) + \frac{\partial}{\partial x}\left(A_H\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V\frac{\partial v}{\partial z}\right) + \sigma(v - v_0)$$

where f is the Coriolis parameter, g is the acceleration of gravity, ρ is the water density, ρ_0 is the reference water density, and A_H and A_V are the horizontal and vertical eddy diffusivities, respectively. A_V is calculated using a standard second order turbulence closure model (based on the Mellor-Yamada 2.5 level scheme -- Kantha and Clayson, 1994), and A_H is set to a constant which may be calibrated. We incorporate our near-field plume mixing model through A_H.

Transport equation for temperature:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(D_H\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V\frac{\partial T}{\partial z}\right) + \frac{1}{\rho_0 c_p}\frac{\partial I}{\partial z} + \sigma(T - T_0)$$

where T is temperature, D_H and D_V are horizontal and vertical eddy diffusivities, respectively, c_p is the specific heat of water, and I is downward solar irradiance. D_H and D_V are proportional to A_H and A_V, respectively.

Transport equation for each passive tracer:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(D_H\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V\frac{\partial C}{\partial z}\right) + \sigma(C - C_0)$$

where C is tracer concentration.

Within each computational cell receiving a portion of the effluent from LSC, IAWWTF, or CHWWTF, σ is set to the volumetric flow rate discharged into that cell divided by the cell volume, and u_0, v_0, T_0, and C_0 are specified based on the diffuser and effluent properties. Within the cells containing the LSC intake and the Bolton Point water treatment plant intake, σ is set to negative one times the intake volumetric flow rate divided by the volume of the cell, u_0 and v_0 are specified based on the intake geometry and the flow rate, and T_0 and C_0 are set to the ambient values (i.e., there is no sink in the equations for T or C).

3.4.2 Near-Field Entrainment

The processes that occur within the acceleration zone of the LSC outfall – contraction and acceleration of the plume – are captured by the equations of Si3D, hence, provided that the near-field plume is well-resolved by the model grid, nothing beyond addition of the source terms to the governing equations is necessary to correctly predict back entrainment and flow within the acceleration zone. Far field mixing and buoyant processes are also captured by the governing equations of Si3D. Within the intermediate field, however, A_H must be modified to achieve linear spreading of the plume and the corresponding downstream growth of dilution. We found that setting

$$A_H = \alpha\sqrt{x - x_V}\exp\left(\frac{y^2}{B_{50}^2(x - x_V)^2}\right)$$

downstream of the diffuser, where α is an empirical constant, results in the desired linear spreading within the intermediate field.

3.4.3 Calibration and Testing of Point Source Model

We are testing the near-field model within Si3D by (1) comparing model predictions for discharge into a large rectangular domain to the analytical solution for a 2D jet in an infinite domain, and (2) comparing model predictions with detailed measurements of temperature in the near field during the August 15-16, 2014 gridding study. We will use the gridding measurements to calibrate the empirical constant α.

In Figure 3-9, we plot preliminary results for the performance of Si3D compared to the analytical solution for a 2D jet in an infinite domain. The numerical solution does not reach steady state because of reflection of waves from the boundaries, and the back entrainment strength appears to be very sensitive to these wave reflections. We are incorporating a sponge layer into Si3D to solve this problem. These results are not converged and are not final. We can see, however, that in the intermediate field, the jet spreads linearly, as desired.

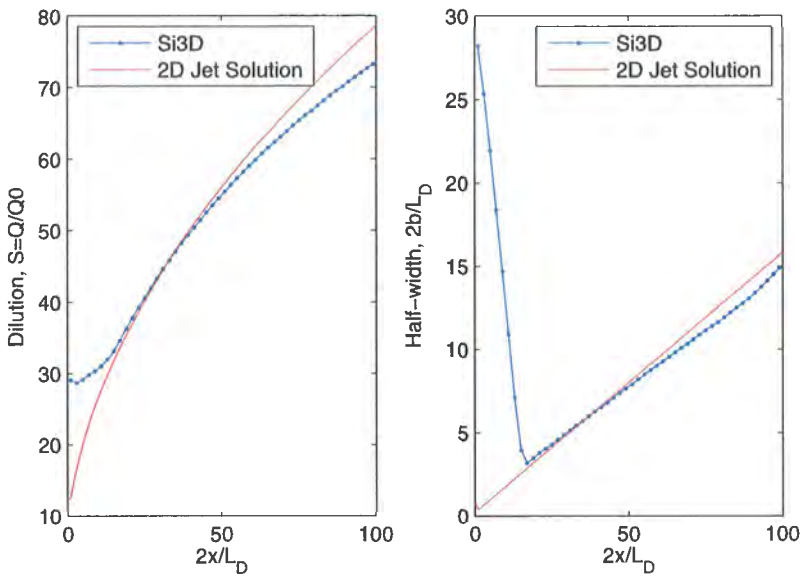

Figure 3-9. Comparison of Si3D predictions to analytical solution for a 2D jet discharging into an infinite domain

3.4.4 Preliminary Validation of Si3D

When the near-field model is fully tested and calibrated, Si3D will be validated by comparing water surface elevation and temperature predictions with field measurements. Comparisons for a pilot model run, using the 125m x 125m mesh only and a non-finalized value of α, are shown in Figures 3-10 and 3-11. Future progress reports will include statistical analysis comparing the fully-tested and calibrated model to the validation data sets.

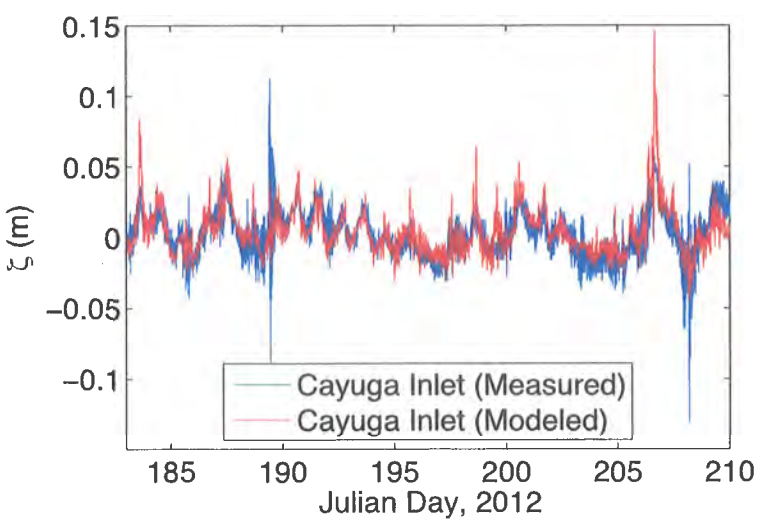

Figure 3-10. Comparison of measured and modeled water surface elevation in Cayuga Inlet in 2012.

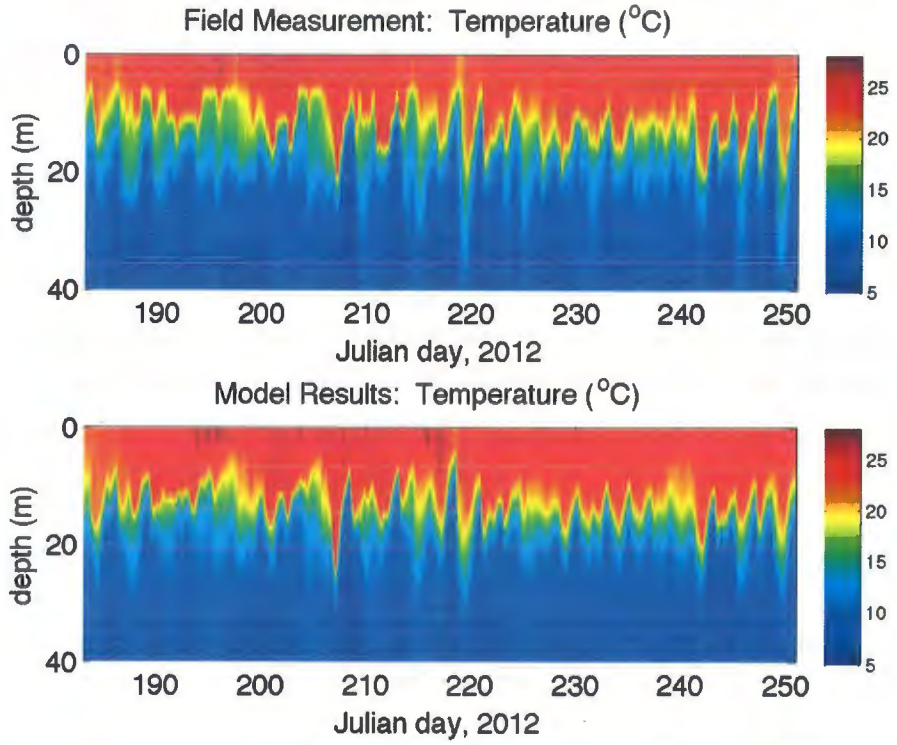

Figure 3-11. Comparison of measured and modeled temperature profiles near LSC intake site in 2012. Color represents temperature in °C.

3.5 Residence Time Experiments

3.5.1 2012 Conditions

Using the 2012 simulation described in the previous section, we conducted some preliminary computational experiments to measure shelf-wide residence time. On July 5, July 20, August 5, August 20, September 5, and September 20, passive tracer was released instantaneously in a uniform distribution across the shelf, defined here as everything south of the 8m isobath. The fraction of the initial mass of tracer remaining on the shelf (M) was tracked in time (t) for 24 days. An exponential tail was fit to M(t) and used to extrapolate until M(t) reached 10^{-6}. The mean residence time (T_R) of tracer on the shelf was then calculated from the formula

$$T_R = \int_0^\infty \frac{dM}{dt} t \, dt'$$

(Hilton et al., 1998; Monsen et al., 2002). These tracer experiments were conducted for three conditions (1) with the LSC outfall as built, using the near-field mixing model, (2) with the LSC outfall discharging 200m north of the 303d line along the intake path, without a near-field mixing model, and (3) without the LSC system. In Figure 3-12 we show the M(t) curves. Legends give the mean residence time and also the e-folding time (EFT), which is the time at which fraction 1/e of the initial mass remains. While a direct comparison cannot be made because the definition of "shelf" was slightly different, these time scales are the same order of magnitude as shelf residence times estimated by Gelda et al. (2014) using their two-dimensional model of Cayuga Lake.

If the shelf were well mixed, the mean residence time and the e-folding time would be equivalent. Hence, these preliminary studies show that the shelf is typically not well-mixed – mean residence time is up to ten times the e-folding time, indicating strong heterogeneity across the shelf. This supports the need for a three-dimensional model. These preliminary results also show that typically the LSC outfall, as built, decreases shelf residence time, but it can sometimes increase shelf residence time. Further experiments employing the nested grid and calibrated near-field model will provide statistics of the impact of the as-built LSC outfall over a wider range of meteorological conditions on both shelf-wide residence time (as reported here) and on residence times of water at the long-term LSC monitoring sites.

During all of these 2012 numerical tracer releases, stream flow was moderate (below $3m^3/s$ total from the southern tributaries). Exchange between the shelf and the greater lake basin was driven primarily by wind-induced internal wave activity. In the next section, we explore the relative importance of tributary flow and internal waves in controlling residence time.

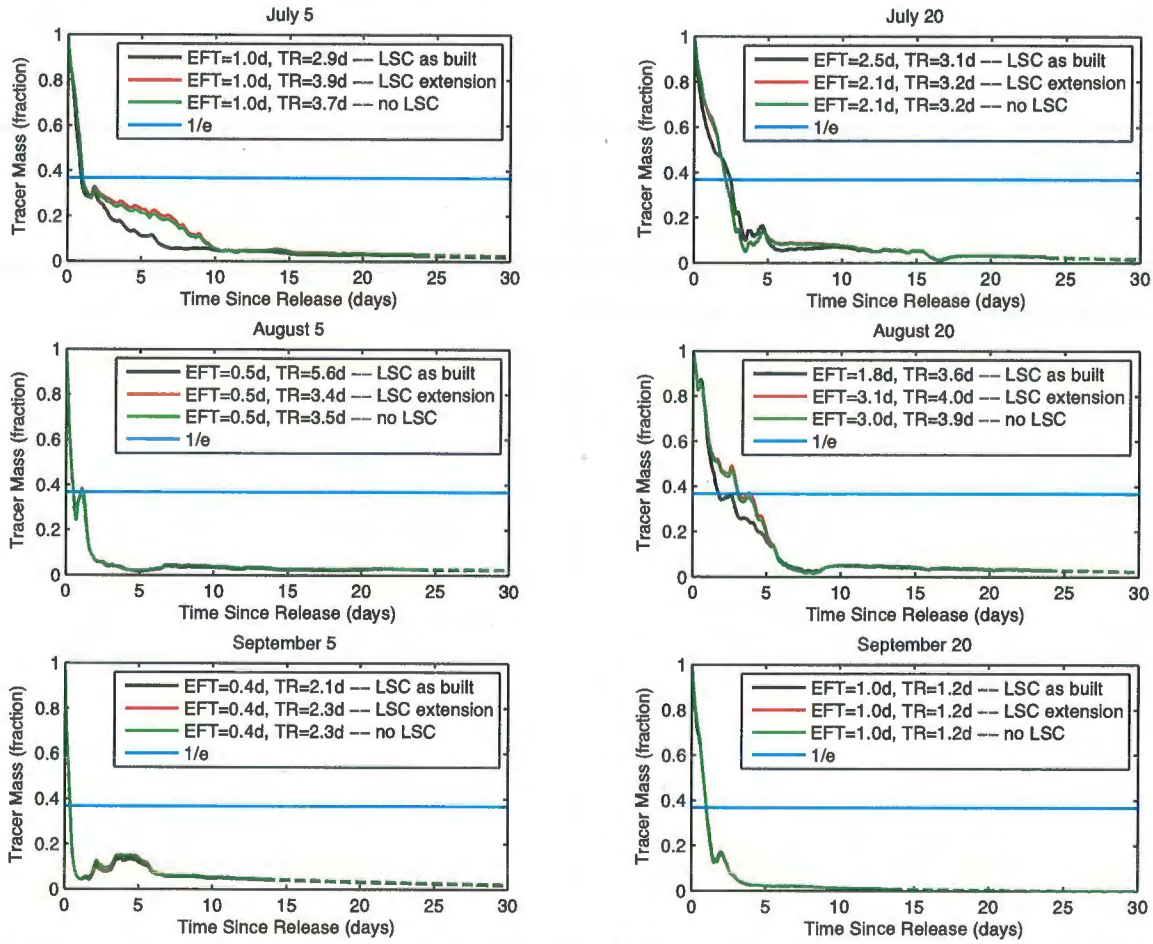

Figure 3-12. Results of preliminary 2012 computational shelf-wide residence time experiments Legends show e-folding times (EFT) and mean residence times (T_R) for the shelf. Plot titles indicate tracer release dates.

3.5.2 Idealized Scenarios

Shelf-wide residence time experiments were also conducted for some idealized scenarios. Again, tracer was released instantaneously over the entire shelf, defined by the 8m isobath. In these experiments, the tails of M(t) were not extrapolated, so residence time estimates are lower bounds. The five idealized scenarios are described in Table 3-3. The "stratified" condition was a 15m epilimnion at 25°C over a hypolimnion at 4°C and the "unstratified" condition was a uniformly 4°C lake. The baroclinic wave period for the stratified condition is Tbc=44hr. For the windy scenarios, wind impulses lasted 33 hours (for duration 0.75Tbc), and the tracer was released instantaneously after 22 hours of wind (at time 0.5Tbc). We used wind speeds of 7m/s and 2m/s, which are, respectively the 99th percentile and 77th percentile 33-hour average wind speeds to the north along the lake axis (based on piling cluster wind measurements). For the tributary-driven scenarios, tracer was released at time zero. The high-flow

tributary-driven scenario is based on the 90th percentile total flow rate from the southern tributaries, 25 m^3/s (1990-present). For each scenario, we tested four conditions: with and without the LSC outfall and with and without the Coriolis force. Results are shown in Figures 3-13, 3-14, and 3-15. In Figure 3-16 we show the effect of tracer release time relative to internal seiche phase on the mean residence time for Scenario B.

Table 3-3. Idealized scenarios for residence time experiments

Scenario	Stratification Condition	Wind	Streamflow
A	Unstratified	7 m/s 33-hr impulse	0
B	Stratified	7 m/s 33-hr impulse	0
C	Stratified	2 m/s 33-hr impulse	0
D	Stratified	0	1.5 m^3/s
E	Stratified	0	25 m^3/s

These preliminary results suggest that wind-driven circulation is the primary mechanism flushing the southern shelf. Stratification, via internal waves, strongly enhances the effect of wind on flushing. In cases where internal wave activity is low and the shelf is flushed primarily by the tributaries, the LSC outfall appears to strongly reduce the shelf residence time. These results are preliminary, but provide insight for further investigation, which will likely include analysis of lower wind speeds that are more representative of typical wind conditions.

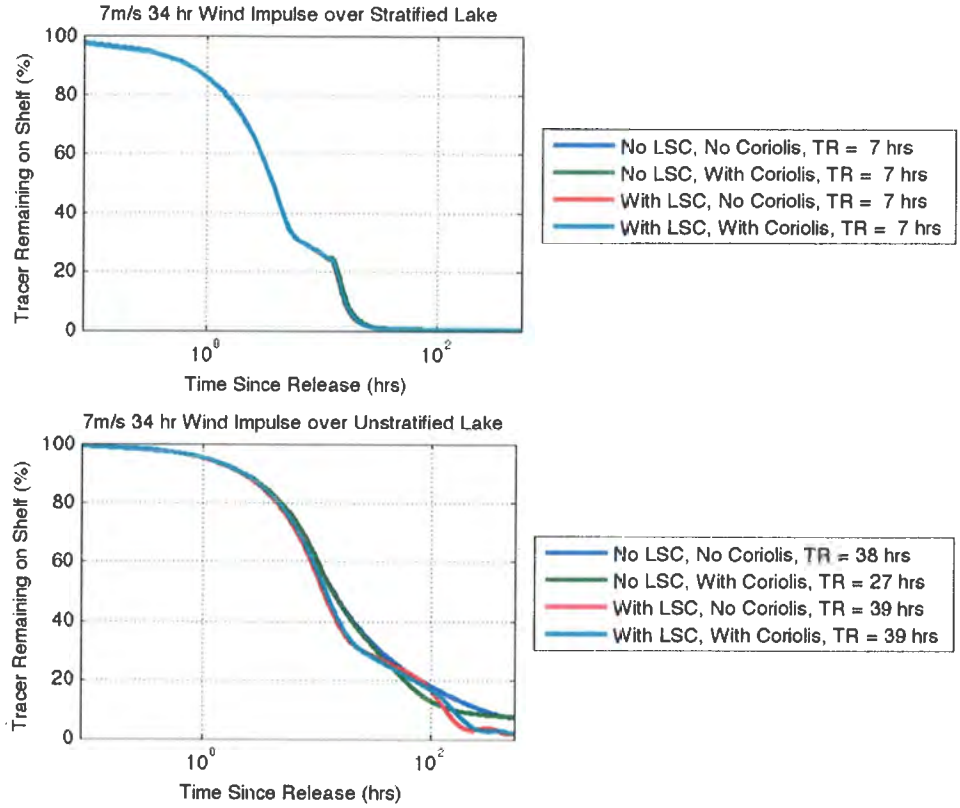

Figure 3-13. Comparison of mean shelf residence time (T_R) for scenarios A (bottom) and B (top).

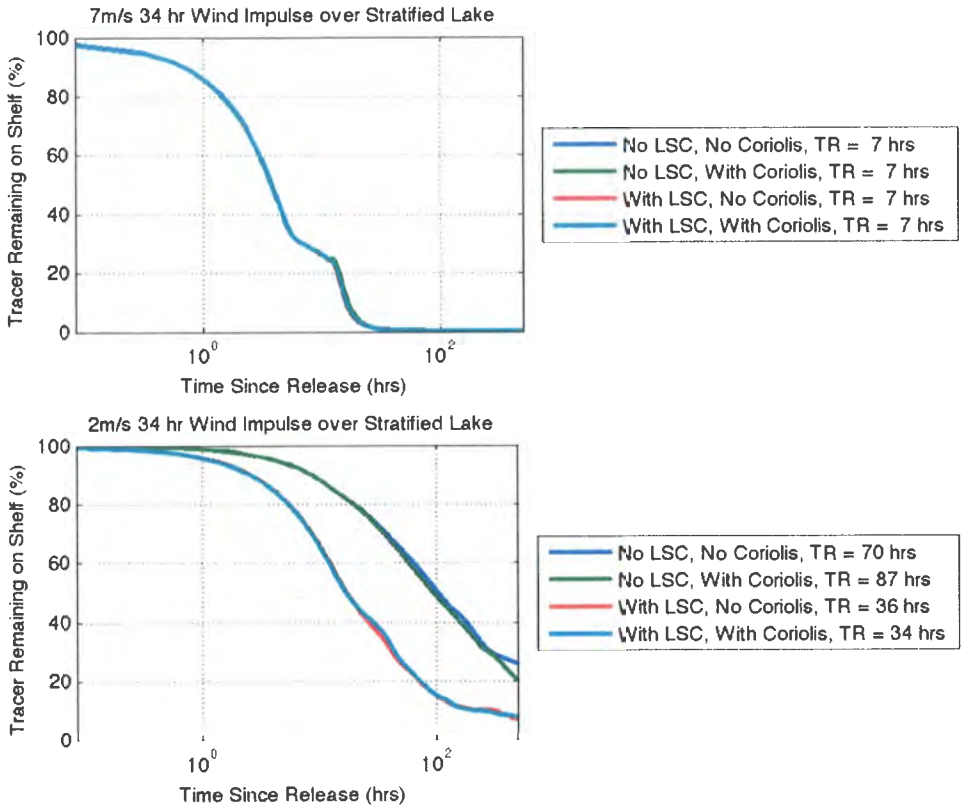

Figure 3-14. Comparison of shelf residence time (T_R) for scenarios B (top) and C (bottom).

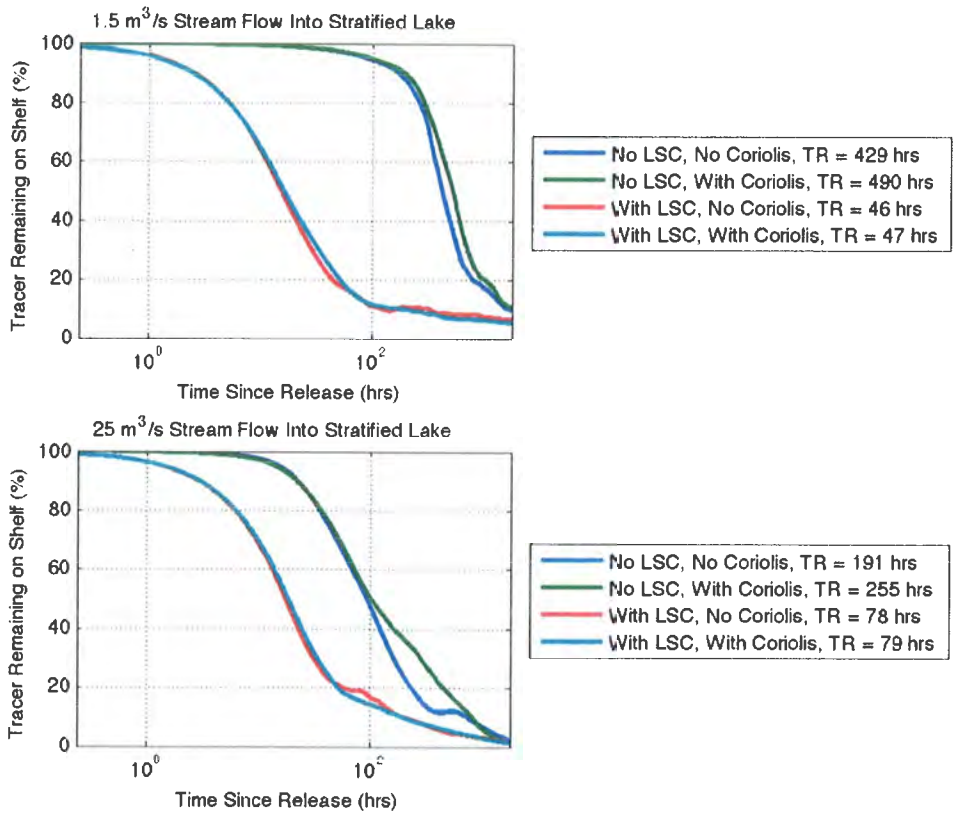

Figure 3-15. Comparison of mean shelf residence time (T_R) for scenarios D (top) and E (bottom).

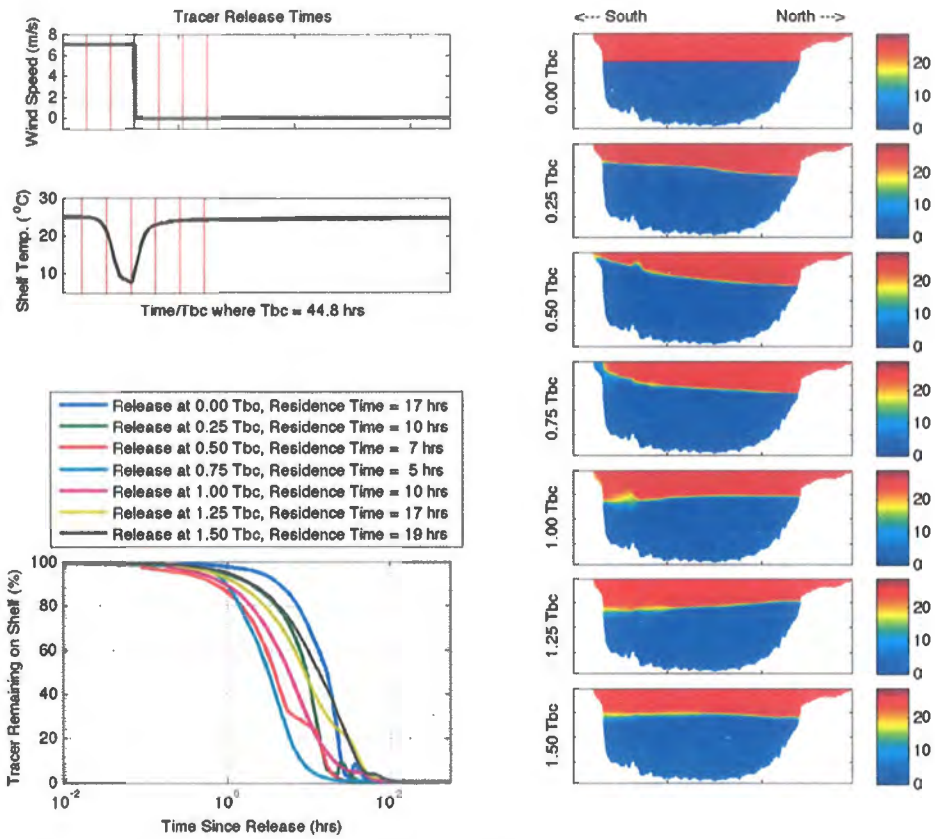

Figure 3-16. Effect of tracer release time relative to baroclinic seiche phase on mean residence time for scenario B. Seiche is illustrated on the right at different phases – color indicates temperature in °C, vertical axis is not to scale. Tbc = 44hrs is the baroclinic wave period.

4. Photic Zone Calculations

4.1 Background

The 2013 SPDES permit for the LSC facility includes a requirement to identify an alternative outfall location within the Class AA segment of Cayuga Lake (i.e., north of the 303(d) line) where the LSC return flow would remain below the photic zone. Photic zone is defined as the depth where 1% of the photosynthetically active radiation (PAR) striking the lake surface remains detectable; this definition is widely used in limnology and oceanography. Photic zone depth is affected by materials dissolved and suspended in the water column that affect light penetration; particulate materials are variable over space and time. UFI measured the depth of light penetration in regions of Cayuga Lake over a nine year period (1998-2006) in support of their research and monitoring efforts. For most years, biweekly measurements are available over the April – October interval. The historical data were supplemented with additional light profile measurements collected in 2013 (July – September). This pooled data set provides a basis for a statistical definition of the photic zone. As described in the approved project work plan, the critical photic zone depth is defined as the upper 75% of the pooled observations from the ten years of light profile measurements.

4.2 Light Profile Data Sources

The historical LSC monitoring program included frequent light profile measurements at three locations within the Class AA segment of Cayuga Lake: sites 6, 8, and LSC (Figure 4-1). UFI scientist Tony Prestigiacomo completed a statistical comparison of data from the three sites and concluded that there was no significant difference between the sites with respect to the depth of light penetration (Figure 4-2). Site 6 is located just north of the 303(d) line within the Class AA segment of Cayuga Lake and in general alignment with the intake pipeline. We used the Site 6 data as a basis for the calculations of critical photic zone depth.

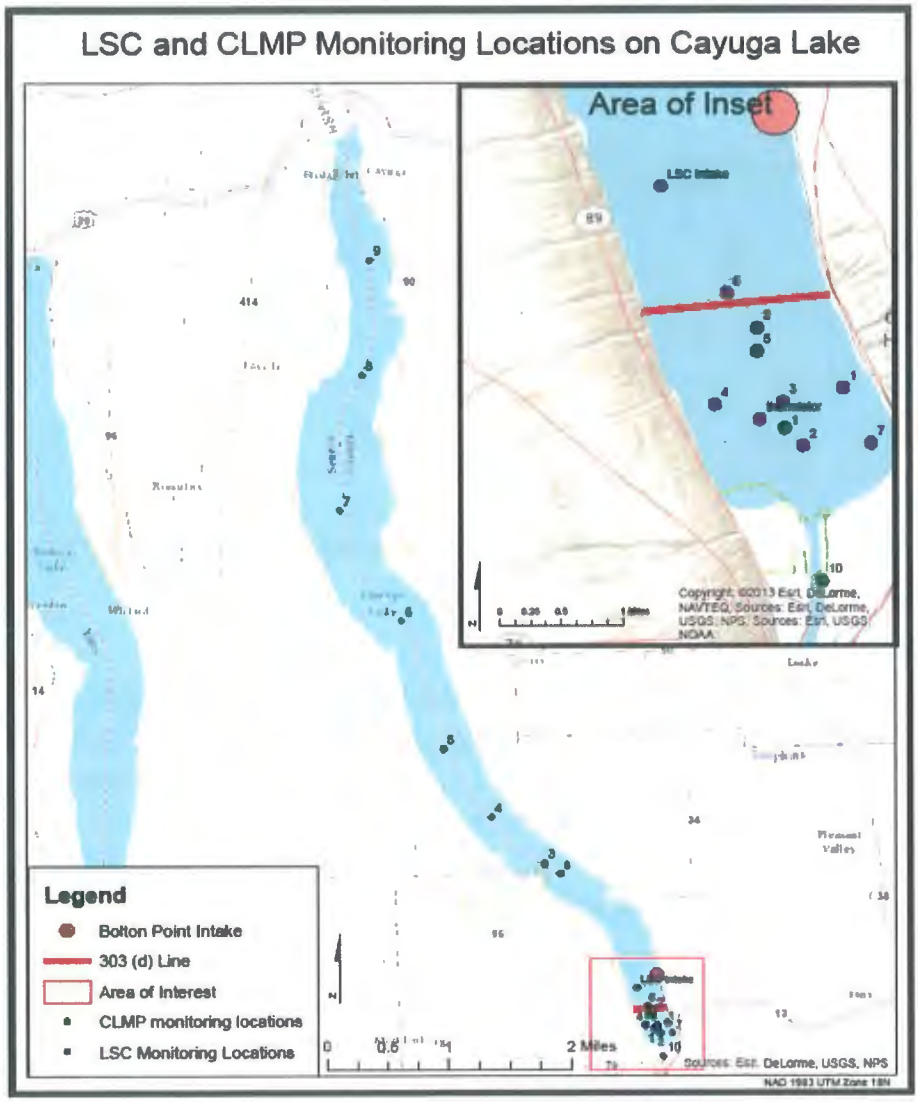

Figure 4-1. Location map of Cayuga Lake monitoring locations showing Site LSC6

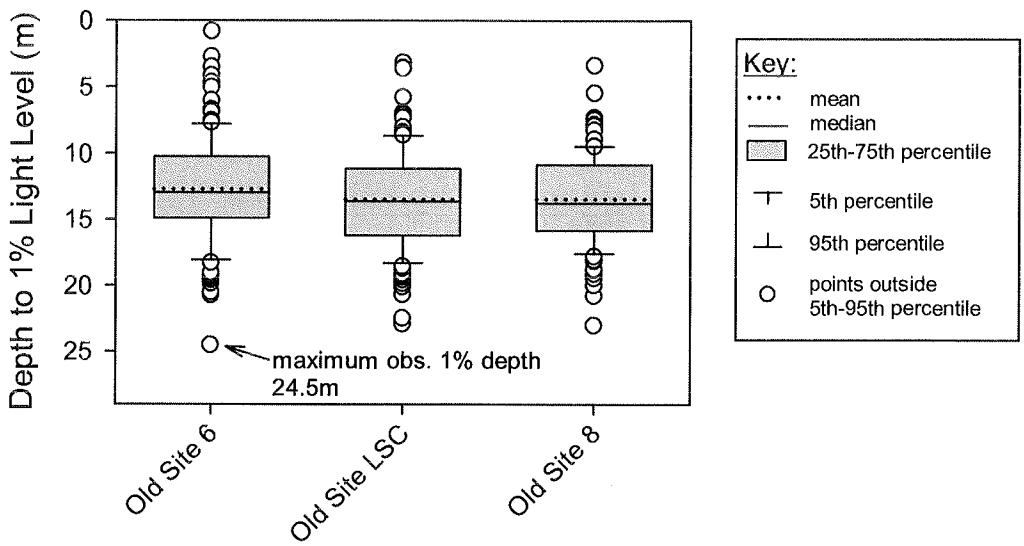

Figure 4-2. Box and whisker plots of photic zone, sites 6, 8, and LSC, 1998-2006

An example profile of downwelling irradiance (I_d; $uEm^{-2}s^{-1}$) from Site 6 is provided in Figure 4-3. The attenuation, or extinction coefficient for downwelling irradiance (k_d; m^{-1}), is determined as the slope of the regression of the natural logarithm of I_d on depth (z). The depth where 1% of ambient light is detected in the water column ($Zl_{0.01}$) is calculated according to the Beer-Lambert Law:

$$I_{d(z)} = I_{d(0)}\, e^{-kd \cdot z}$$

Manipulation of this expression for the 1% light level case (in which $I_{d(z)} \div I_{d(0)} = 0.01$) yields the following expression for $Zl_{0.01}$:

$$Zl_{0.01} = 4.6052 \div k_d$$

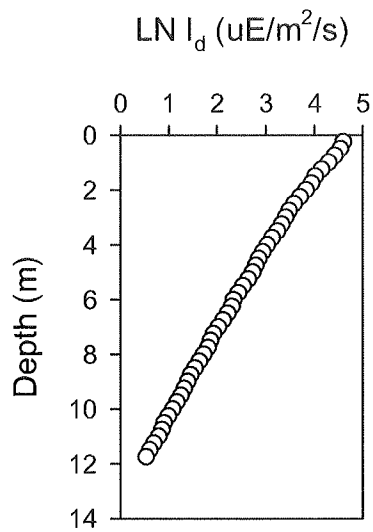

Figure 4-3. Example light profile (LN transformed) from Old Site 6, October 26.

4.3 Results

The ten years of light profile measurements collected by UFI on Cayuga Lake have been analyzed to define the statistical distribution of the photic zone. The approved workplan defined the critical period for light penetration as June 1 – September 30, which is consistent with the NYSDEC regulatory approach for protection of recreational uses of lakes. However, NYSDEC has requested additional evaluation and discussion of the potential for the LSC return flow to reach the photic zone during the months of May and October; this request reflects the fact that NYSDEC is considering promulgating nutrient criteria for protection of public water supplies, and the period of compliance may extend beyond the June 1 – September 30 averaging period.

To comply with this request, the statistical analysis of Cayuga Lake light profiles was expanded to include data collected in May and October. As shown in Table 4-1, the upper 75% of the photic zone depth is calculated to be 13.55 m during the summer months (June 1- Sept 30). When May and October (the shoulder months) are included in the statistical calculation, the upper 75% of the photic zone extends to a depth of 14.9 m.

Table 4-1. Calculated photic zone depth at LSC site 6 from light profiles collected 1998-2006 and 2013

Month	Valid N	Mean (m)	Median (m)	Min (m)	Max (m)	Upper 75% (m)	Std. Dev.
May-Oct.	136	12.62	12.67	0.81	24.5	**14.90**	4.1
June-Sept.	85	11.66	11.33	0.81	24.50	**13.55**	4.00
May	14	13.31	14.34	3.49	19.85	**17.05**	4.20
June	18	12.99	13.58	0.81	20.72	**16.66**	5.30
July	20	10.35	9.72	2.72	18.06	**11.55**	3.64
Aug.	24	10.30	10.79	4.57	14.95	**11.76**	2.46
Sept.	23	13.16	12.97	8.06	24.50	**13.69**	3.49
Oct.	10	14.07	14.19	10.26	18.03	**14.90**	2.07

5. Identify an Alternative Discharge Location That Meets Criteria

In the workplan, we proposed using the validated 3D model to evaluate the 12-day rolling average location of the mixing zone of the LSC outfall for an alternative discharge location. We are to evaluate at least one location and try different locations to the north or south, if necessary, to minimize discharge pipe length while ensuring that the mixing zone remains below the photic zone. The mixing zone is defined as the region ≥3.0°F (1.67°C) above ambient temperature. The extended outfall pipe would run parallel to the existing intake pipe and discharge in that direction, which is 36° west of true north. In Figure 5-1 we provide a map of the intake pipeline showing its angle and the lake bathymetry in its vicinity.

The proposed specification for the outfall in the workplan was a 57in inner-diameter single port pipe located 1m to 5m above the lake bottom and discharging to the north. Preliminary analysis of pipe availability and material properties indicates the suitability of 63in DR26 HDPE pipe, which has inner diameter 57.9in (1.47m). This type of pipe, if run along the path of the intake pipeline to a location 200m north of the 303d line, could be propped 3m above the bed such that the discharge direction is angled 12° above the horizontal plane. We use this 3m height above the bed and 12° discharge angle for the preliminary mixing zone evaluations reported here.

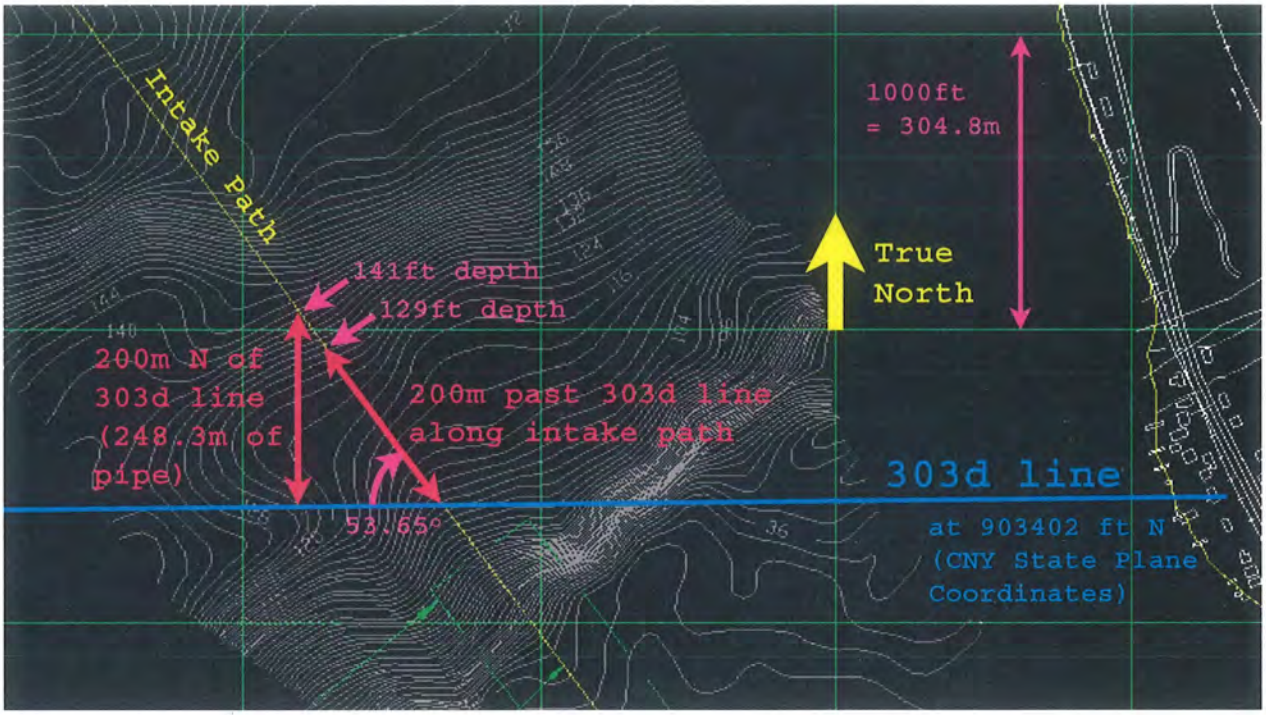

Figure 5-1. Annotation of as-built drawing 1142LB01 to show angle of intake pipeline path and depth contours along the intake pipeline path north of the 303d line. General notes found in the as-built drawings say "bathymetry contour depths shown are relative to lake level of 383.05' (subtract 0.68' to make relative to mean summer lake level of 382.37')", and this applies to the contours shown here in white and the two depths indicated in magenta. White contour labels are in units of feet. Horizontal scale is same as vertical scale.

Before undertaking the 3D modeling task, we used CORMIX I (Doneker and Jirka, 1990) a USEPA-supported mixing zone model appropriate for single-port discharges, to evaluate the location of the mixing zone for three different scenarios. These scenarios were selected to represent worst case conditions based on

a) historically observed and design (assuming perfect heat exchangers) operating parameters of the LSC system, and
b) the worst possible ambient conditions at the discharge site, meaning ambient conditions that result in the greatest rise of the discharge plume.

To determine a worst-case scenario based on historical data, we examined statistics of effluent flow rate, intake temperature, and effluent temperature, based on hourly measurements at the LSC Heat Exchange Facility (HXF) collected with a continuous monitoring system since 2005. These statistics are shown in Figure 5-2.

Note that the maximum daily permitted flow rate through the LSC facility is set in the SPDES permit at $2.0 m^3/s$, and the maximum observed hourly flow rate is close to this value. Because the LSC intake is

deeper than any proposed location of the extended outfall, observed intake temperatures provide a lower bound on the ambient temperature expected at the extended outfall site. Intake temperature typically remains close to 4°C throughout the year. Typical summer effluent temperature is around 10°C, and the maximum observed effluent temperature during the operation of the continuous monitoring system was 12.8°C. Plant operators report anecdotally that 12.8°C is also the maximum effluent temperature observed since the LSC system began operating in 2000. Therefore our historically based worst-case scenario employs this historical maximum effluent temperature, 12.8°C.

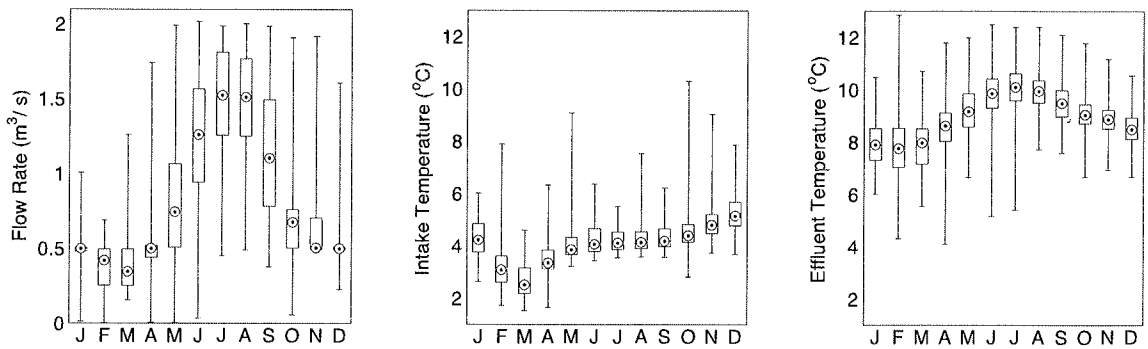

Figure 5-2. Box-and-whisker plots showing month-by-month statistics of flow rate, intake temperature, and effluent temperature, measured hourly at the LSC HXF between January 2005 (when the continuous monitoring system was installed) and August 2013. Circled dots indicate medians, boxes span 25th to 75th percentiles, and whiskers extend to minima and maxima.

To determine a worst-case scenario based on perfectly efficient operation of the LSC system, we considered the design of the current LSC system. The campus chilled water loads are a mixture of old and new cooling coils distributed among the roughly 100 buildings on campus, resulting in a mixed return temperature back to the LSC HXF. The maximum theoretical value of the return chilled water, assuming perfect heat exchangers, is the current design return chilled water temperature of new loads, 16.7°C. This temperature cannot of course ever be achieved in reality, due to the less than perfect performance of real world heat exchangers. The actual typical maximum return chilled water temperature is in the range of 15°C on the hottest days of summer each year, which results in observed maximum effluent temperatures in the range of 12°C. In order to create a design scenario based on a maximum theoretical limit to the effluent temperature well above our current actual effluent temperature, we have selected 16.7°C.

In a third worst-case scenario, we consider 15°C as an intermediate point that illustrates a value about half way between today's historical maximum effluent temperature and the theoretical maximum based on perfect heat exchangers. This third example illustrates the sensitivity of the plume rise to effluent temperature.

The plume rises to its maximum height when effluent buoyancy is maximized. Maximum effluent buoyancy occurs when the ambient temperature of the receiving water is 4.0°C (the temperature at which fresh water is most dense) and the effluent temperature is maximal. Turbulence due to ambient

current and surface wind stress dilutes the effluent plume, so wind and ambient currents are zero in the worst-case ambient conditions. The effect of flow rate on mixing is less straightforward; higher flow rate increases buoyancy flux, which increases the rate of plume rise, but also increases mixing, which dilutes the plume as it rises.

CORMIX I parameters used for our "Historical", "Intermediate" and "Theoretical" design scenarios are shown in Table 5-1. Ambient water velocities and wind speeds were set to zero. A water depth of 42m, distance to right bank of 930m, and Darcy-Weisbach friction factor of 0.02 were also specified, but since in all cases the mixing zone is contained entirely within the near field of the plume, the CORMIX results are independent of these three parameters. In order to determine the worst-case effluent flow rate for each design case, we tested a range of effluent flow rates between 0.5m^3/s and 3.0m^3/s, determining that the worst case for the design scenario based on historical effluent temperature is 1.0m^3/s and the worst case for the design scenarios based on theoretical and intermediate effluent temperatures is 1.5 m^3/s (demonstrated in Figure 5-3).

Table 5-1. CORMIX I parameters for worst-case scenarios based on historical maximum observed effluent temperature, theoretical effluent temperature for the current LSC system assuming perfect heat exchanger efficiency, and an intermediate effluent temperature.

CORMIX I parameters	Historical Worst-Case Scenario	Intermediate Worst-Case Scenario	Theoretical Worst-Case Scenario
Outfall diameter	1.47m	1.47m	1.47m
Height of outfall above bed	3.0m	3.0m	3.0m
Vertical discharge angle	12°	12°	12°
Ambient temperature	4.0°C	4.0°C	4.0°C
Effluent temperature	12.8°C	15.0°C	16.7°C
Effluent flow rate	1.0m^3/s	1.5m^3/s	1.5m^3/s

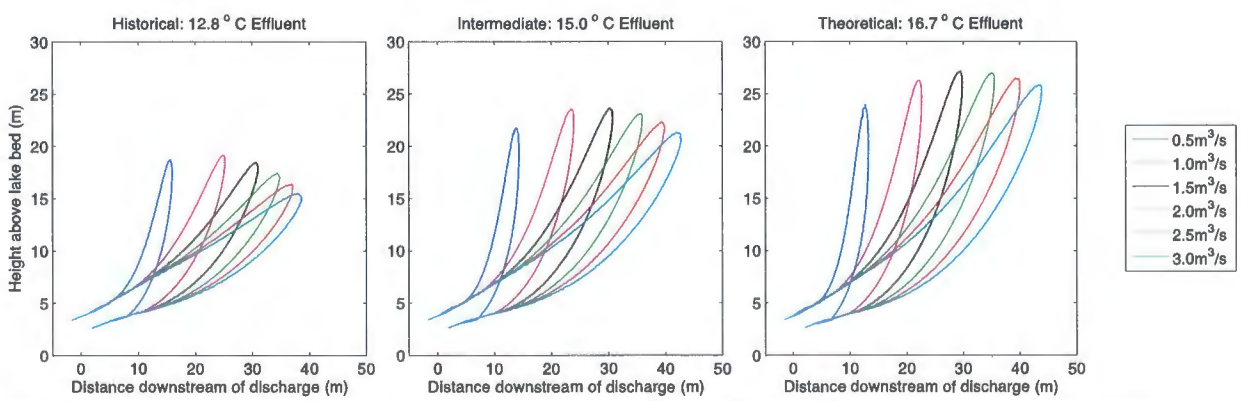

Figure 5-3. Outer contours of mixing zone predicted by CORMIX I for different effluent flow rates tested for "Historical", "Intermediate", and "Theoretical" design cases. CORMIX input parameters used to generate these contours (besides effluent flow rate) are given in Table 5-1. Effluent flow rate

used as CORMIX input for each contour is given in legend. Outer contour of mixing zone is defined as 1.67°C above ambient temperature.

For each design scenario (using worst-case effluent flow rate), we examined lake bathymetry along the intake pipeline path to determine the distance the extended outfall pipeline would have to extend past the 303d line in order to ensure that the mixing zone of the LSC discharge plume remains below the photic zone, as defined in Section 4. Bathymetry along the intake pipeline path is based on depth contours from the as-built survey (see Figure 5-1) and the mean summer lake level of 116.5m. In Table 5-2 we report the distance north of the 303(d) line, the length of pipe past the 303(d) line, and the depth of the lake bottom at the outfall location required by each worst-case design scenario to ensure that the mixing zone remains below the photic zone. In Figure 5-4, we illustrate the mixing zone relative to the lake bottom and photic zone depth for each worst-case design scenario with the outfall placed at the location specified in Table 5-2. In this analysis we have used the photic zone defined by June-September statistics; in Appendix A we show the results of using the photic zone defined by May-October statistics. Recall that only the first scenario is feasible given the current configuration and operation of the LSC facility. The intermediate and theoretical scenarios are included to illustrate the sensitivity of the model output to the initial assumptions.

Table 5-2. Specifications for outfall location required to ensure the LSC discharge plume mixing zone remains below the photic zone.

Specifications for Outfall Location	Historical Worst-Case Scenario	Intermediate Worst-Case Scenario	Theoretical Worst-Case Scenario
Distance north of 303(d) line	43 m	138 m	180 m
Length of pipe past 303(d) line	53 m	172 m	223 m
Lake bottom depth at outfall site	32.8 m	37.2 m	40.8 m

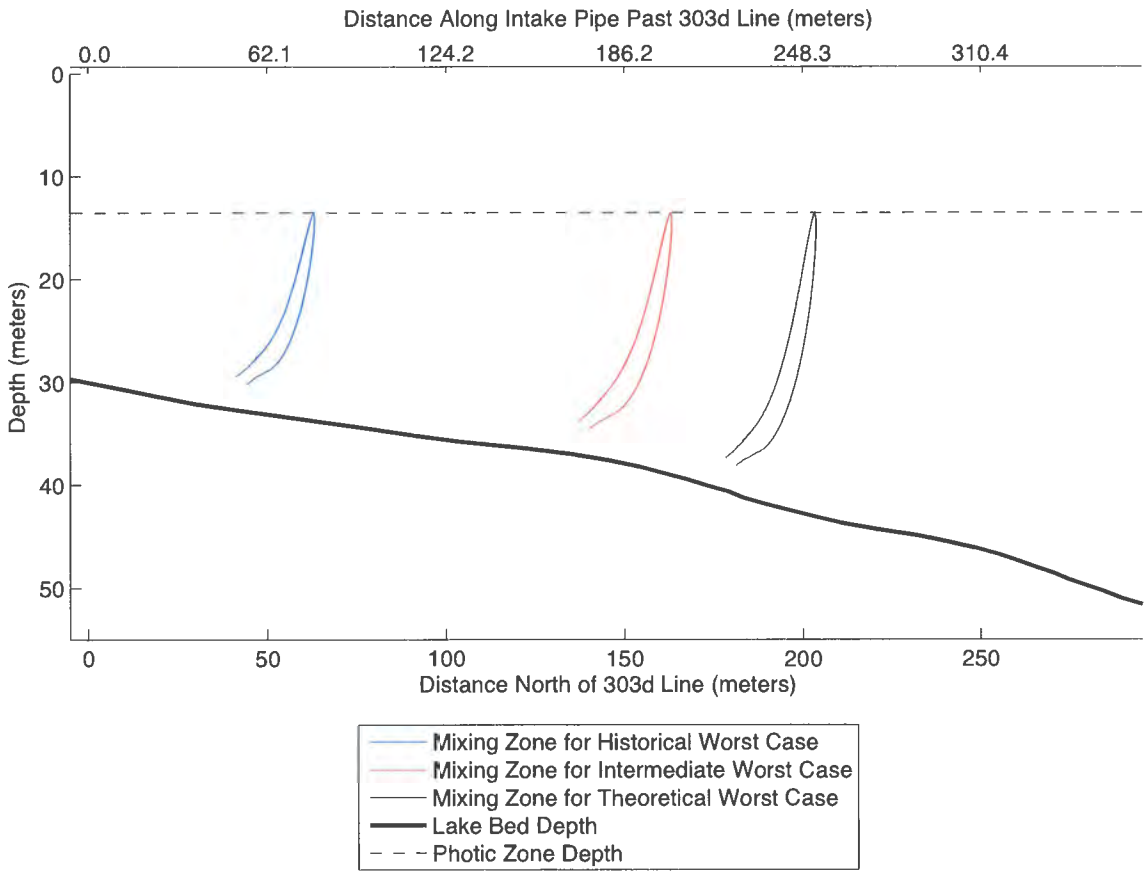

Figure 5-4. Outer contours of mixing zone predicted by CORMIX I for each of three design scenarios (specified in Table 5-1). Scenario 1 (historical worst case) is realistic; the other two were modeled as part of a sensitivity analysis. Outer contour of mixing zone is defined as 1.67°C above ambient temperature. Mixing zone location is illustrated relative to the lake bed and the photic zone (defined in Section 4) with the outfall placed at the location specified in Table 5-2, which is the location required to ensure that the mixing zone remains below the photic zone. In all cases, the outfall is located along the intake pipeline path (shown in Figure 5-1) north of the 303(d) line. On the plot axes, distance past the 303(d) line is specified both as distance north (lower axis) and as distance along the intake pipeline path (upper axis).

Using the 3D model and/or historical records from deep-water thermistor strings and the piling cluster meteorological station (described in Section 3) to evaluate more realistic ambient conditions at the alternative discharge site will only lead to more favorable predictions of the mixing zone location, since ambient stratification arrests the rise of the plume, and ambient current and wind increase dilution rate. Hence, we believe it is unnecessary to involve the 3D model or historical records of ambient meteorological conditions in the evaluation of an alternative discharge location provided that the outfall pipeline is extended to the location recommended by a CORMIX I analysis of a worst-case design

scenario such as one of the cases presented in this section. We will discuss with NYSDEC what design scenario is appropriate as Cornell Energy & Sustainability leadership considers the future of the LSC system. If the Cornell team is satisfied with the recommended outfall pipeline length, we intend to rely entirely on this type of CORMIX-based worst-case scenario analysis. However, if it is advantageous to install a shorter outfall pipeline, we reserve the option approved by NYSDEC in the workplan to use the 3D model and/or field data to determine a more realistic and less conservative, but still appropriately conservative, design scenario.

6. Problems Encountered and Impact on Schedule

None. We have incorporated the NYSDEC request to include the months of May and October in our analysis of critical photic zone depth. We have demonstrated that it is possible to use CORMIX 1 to identify an alternative discharge site north of the 303(d) line that would ensure the LSC return flow would remain below the photic zone between May and October under all feasible conditions of water column stratification, ambient currents, and wind conditions. The alternative discharge site location identified using CORMIX 1 will be determined by the design criterion chosen for LSC effluent temperature. This finding enables us to omit setting up the three-dimensional model Si3D for the relocated outfall scenario, unless it is determined by Cornell University that a shorter outfall pipeline is necessary. Completion of this analysis within the first eight month reporting period has had a positive impact on schedule.

7. Upcoming Tasks

- Continue the set-up and validation of Si3D model of the existing outfall
- Calculate the residence time of water spanning the lake's southern shelf with and without the LSC return flow for a range of observed meteorological conditions
- Calculate the residence time of water at the LSC long-term monitoring sites with and without the LSC return flow for a range of observed meteorological conditions
- Document the effective transfer of water between the 303(d) listed segment and the rest of Cayuga Lake for a range of meteorological conditions
- Select a consultant to assist Cornell with the following workplan tasks related to the outfall relocation and redesign:
    - Develop (engineers opinion of) costs for permitting, design, survey, bidding, construction
    - Identify potential suppliers and contractors; develop critical path timeline for acquisition of pipe and other materials.
    - Identify required regulatory permits and approvals from NYSDEC, ACOE, and any local municipalities; including SEQRA compliance
    - Identify required easements from Office of General Services

8. References

Akar, P.J.; Jirka, G. H. (1991). CORMIXII: An expert system for hydrodynamic mixing zone analysis of conventional and toxic multiport diffuser discharges. Technical report, United States Environmental Protection Agency. EPA/600/3-91/073.

Doneker, R.L.; Jirka, G.H. (1990). Expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged single port discharges (CORMIX I). Technical report, United States Environmental Protection Agency. EPA/600/3-90/012.

Gelda, R.K.; King, A.T.; Effler, S.W.; Schweitzer, S.A.; Cowen, E.A. (2014). Manuscript submitted for review to Inland Waters.

Gill, A.E. (1982). Atmosphere-Ocean Dynamics. San Diego: Academic.

Haith, D.A.; Hollingshead, N.; Bell, M.L.; Kreszewski, S.W.; Morey, S.J. (2012). Nutrient loads to Cayuga Lake, New York: Watershed modeling on a budget. J. Water Res. Plann. and Manage. 138:571-580.

Hilton, A.B.C.; McGillivary, D.L.; Adams, E.E. (1998). Residence time of freshwater in Boston's inner harbor. J. Water Port Coast. Ocean Eng. 124:82-89.

Kantha, L.H.; Clayson, C.A. (1994). "An improved mixed layer model for geophysical applications". J Geophys Res, 99(C12):25235-25266, doi:10.1029/94JC02257.

Monsen, N.E.; Cloern, J.E.; Lucas, L.V.; Monismith, S.G. (2002). A comment on the use of flushing time, residence time, and age as transport time scales. Limnol Oceanogr. 47:1545-1553.

Rueda, F.J. (2001). "A three-dimensional hydrodynamic and transport model for lake environments." Ph.D. Dissertation, University of California, Davis.

Singleton, V.L.; Rueda, F.J.; Little, J.C. (2010). "A coupled bubble plume-reservoir model for hypolimnetic oxygenation." Water Resour Res, 46(W12538), doi:10.1029/2009WR009012.

Smith, P. E. (1997). "A three-dimensional, finite-difference model for estuarine circulation." Ph.D. Dissertation, University of California, Davis.

Vandebroek, E. (2011). "Development of boundary conditions and bathymetry data for modeling transport processes in the southern end of Cayuga Lake." M.Eng. Report, Cornell University.

Appendix A. Analysis of May and October Conditions

As demonstrated in Section 5, the depth to which the return flow plume rises in the water column depends on multiple assumptions related to both facility operations and environmental conditions. CORMIX-based modeling based on worst-case ambient conditions indicates that a return flow discharged at an appropriate location north of the 303(d) line would not rise into the photic zone under feasible operational conditions of the LSC facility. Consequently, additional analysis of the risk of nutrient enrichment and phytoplankton growth would be unnecessary. If more realistic ambient conditions were considered, it is possible that a discharge at any location north of the 303(d) line would be projected to remain below the photic zone.

However, the same set of assumptions related to LSC operation and environmental conditions might require a slightly deeper outfall to accommodate the deeper photic zone calculated using May through October conditions. The modeling assumptions are shown in Table A-1 and the projected rise of the plume is plotted in Figure A-1.

Table A-1. Specifications for outfall location required to ensure the LSC discharge plume mixing zone remains below the photic zone, employing the photic zone definition that includes statistics from May – October (see Section 4).

Specifications for Outfall Location	Historical Worst-Case Scenario	Intermediate Worst-Case Scenario	Theoretical Worst-Case Scenario
Distance north of 303(d) line	70 m	157 m	192 m
Length of pipe past 303(d) line	87 m	196 m	239 m
Lake bottom depth at outfall site	34.1 m	38.5 m	42.1 m

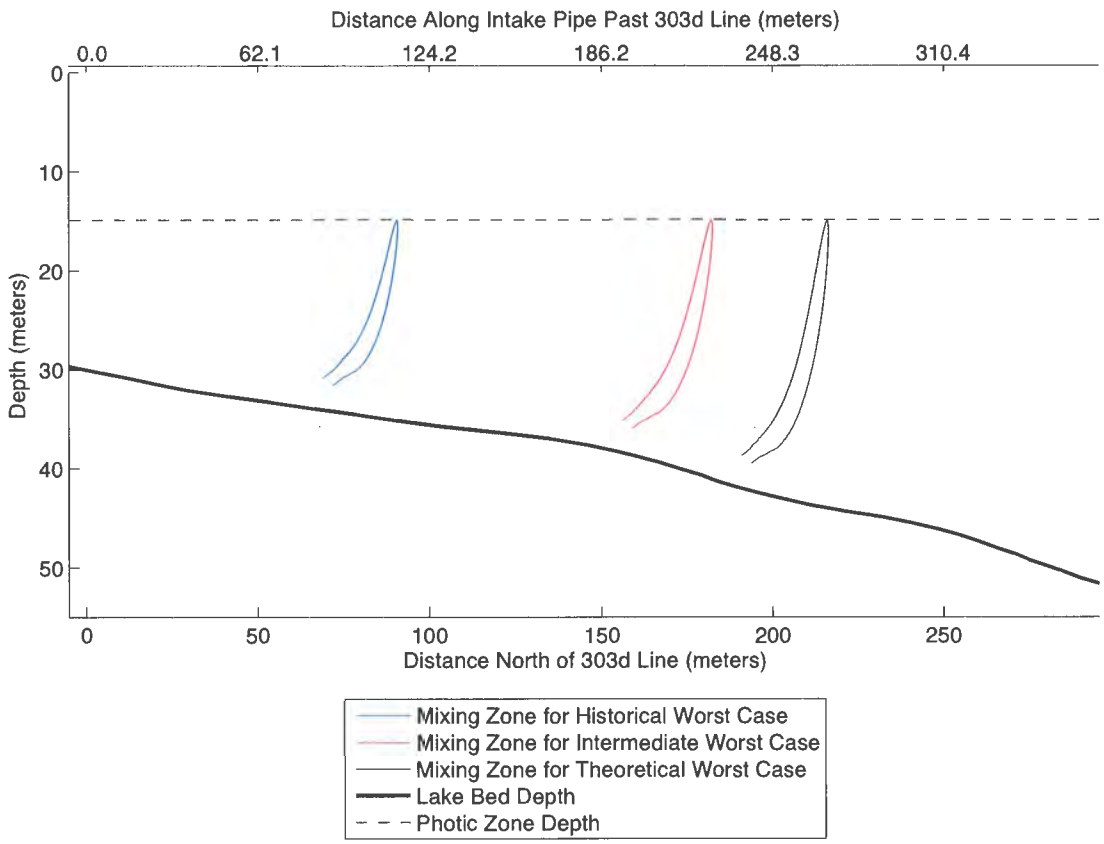

Figure A-1. Outer contours of mixing zone predicted by CORMIX I for each of three design scenarios (specified in Table 5-1). Scenario 1 (historical worst case) is realistic; the other two were modeled as part of a sensitivity analysis. Outer contour of mixing zone is defined as 1.67°C above ambient temperature. Mixing zone location is illustrated relative to the lake bed and the photic zone (defined in Section 4) with the outfall placed at the location specified in Table 5-2, which is the location required to ensure that the mixing zone remains below the photic zone. In all cases, the outfall is located along the intake pipeline path (shown in Figure 5-1) north of the 303(d) line. On the plot axes, distance past the 303(d) line is specified both as distance north (lower axis) and as distance along the intake pipeline path (upper axis).

For several reasons, we do not consider May or October conditions critical to a design criterion developed to protect the lake from nutrient enrichment and phytoplankton blooms resulting from the return flow from the LSC facility.

- The UFI water temperature profiles collected between 1998 and 2006 indicate that Cayuga Lake typically does not exhibit thermal stratification in May (temperature profiles for May and October are displayed in Figures A-2 and A-3). When the lake is not stratified, wind-induced circulation mixes the water column; circulation through the LSC facility represents an additional mechanism for mixing to occur. There is no basis for concern regarding phosphorus circulation

between the intake and outfall regions when the lake is not stratified, as natural mixing processes overwhelm the small volume of water circulated by the LSC facility.

- The demand for campus cooling is also lower during the shoulder months (the monthly volume of water circulated by LSC is shown in Figure 5-2).
- Phytoplankton productivity is reduced by the cold water temperatures and low ambient light conditions found during May and October.

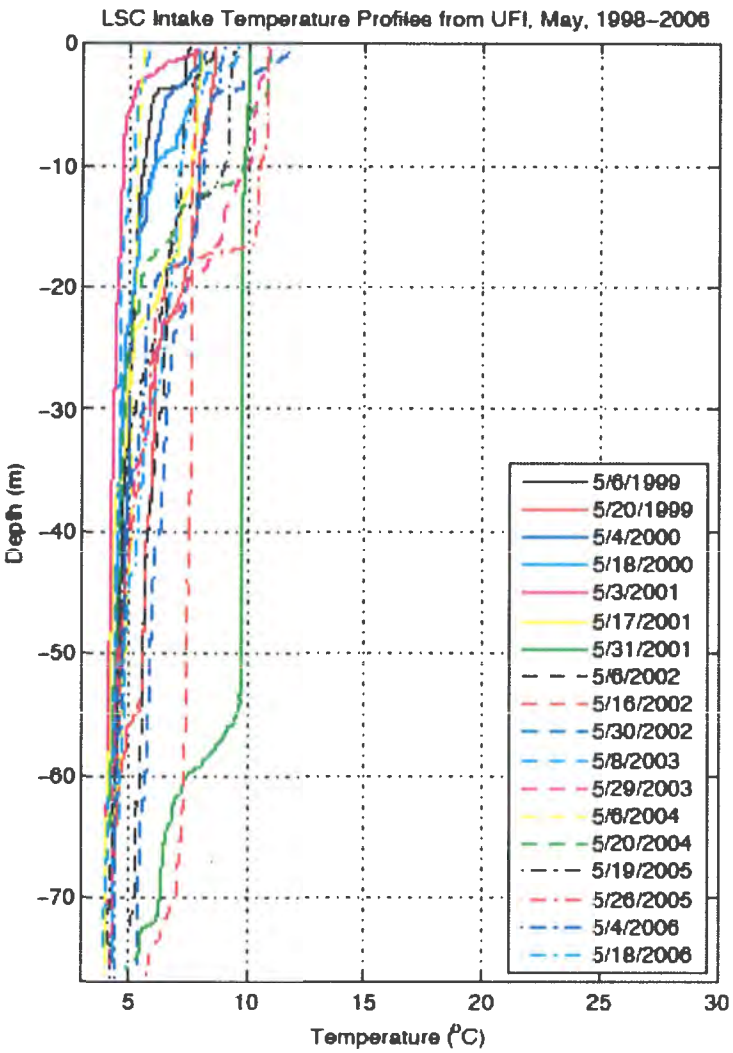

Figure A-2. Temperature profiles of Cayuga Lake measured in the vicinity of the LSC intake on May dates between 1999 and 2006.

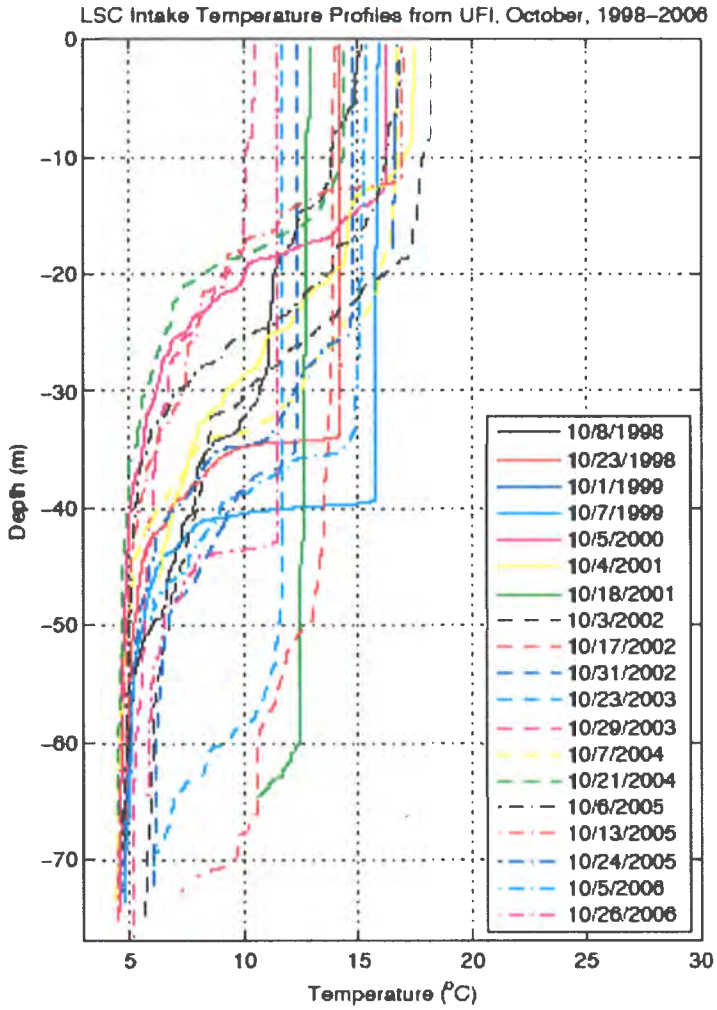

Figure A-3. Temperature profiles of Cayuga Lake measured in the vicinity of the LSC intake on October dates between 1998 and 2006.