Final Report to the New York State Water Resources Institute

Water Quality Assessment using Advanced Technology to Improve Adaptive Management of the St. Lawrence River

Project period: March 1, 2014 - February 28, 2015.

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Project abstract: The project incorporates the development and deployment of a novel and innovative cost-effective observing technology approach that can meet identified data gaps to support the high priority focus area of enhanced ecosystem integrity through improved resource management, as identified in the New York State Great Lakes Action Agenda. A sensor station located in a hydropower dam was established on June 17, 2014 that continuously detects and records nearshore water quality in the St. Lawrence River. Observations of continuous water quality measurements allow tracking and forecasting of climatic, biological and changes in the Great Lakes ecosystem in relation to changes in river hydrology. The project supports data-driven decisions regarding adaptive management and the cost-effective planning of coordinated surveillance and monitoring of these resources and is part of a burgeoning smart infrastructure being developed in the Great Lakes basin to address water resource management.

Project Overview

Statement of project focus: In a rapidly changing world, water resources in the Great Lakes-St. Lawrence system are threatened as ecosystem integrity is challenged. Accordingly, we need to respond rapidly to threats and thus, appropriate tools and approaches are required. According to Annex 10 of the 2012 Great Lake Water Quality Agreement (GLWQA) adaptive management is to be used as a "*framework for organizing science to provide and monitor the effect of science-based management options*". We are working to develop the condition wherein science-based management of connecting channels (i.e. large rivers, such as the Saint Lawrence) is assisted by a data-rich information base provided by riverine sensor arrays. The project incorporates the development and deployment of a novel and innovative cost-effective observing technology approach.

Article 1.c of the revised GLWQA explicitly states that the major rivers (Figure 1), which comprise the natural outflows amongst the Great Lakes, are integral components of the Great Lakes ecosystem and thus, these rivers are now required to be monitored and assessed according to the GLWQA (Annex 2). This is a marked change from the earlier GLWQAs and puts added stresses on increasingly limited budgets and personnel that are now required to add additional resources to meet the new requirements. For the Lake Ontario Lakewide Action and Management (LAMP) this is a particularly acute case. The LAMP must now not only incorporate the Niagara River but also the St. Lawrence River, which alone has a shoreline that *exceeds* that of Lake Ontario. A recent (March 2015) survey of operators of advanced water quality sensors in the Great Lakes-St. Lawrence River (GL-SLR) region shows (Figure 1) that the St. Lawrence River has very few operators capable of supporting new LAMP needs.

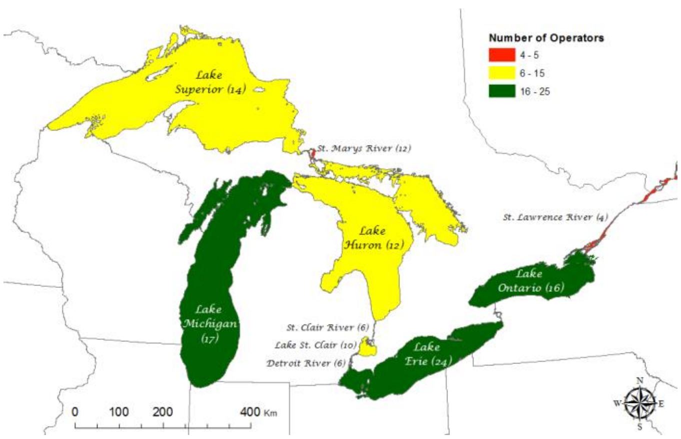


Figure 1. *Number of water quality sensing operations in the Great Lakes region showing that the St. Lawrence is underrepresented despite its size and the need to support adaptive management of this resource.* *<u>Source</u>: Twiss & Stryszowska; unpublished report for the Science Advisory Board of the International Joint Commission.*

The objective of this project is to continuously detect and record nearshore channel water quality in the St. Lawrence River by operating a sensor station in a hydropower dam. In combination with observed water quality measured upstream and hydrodynamic modeling we will determine the extent of upstream river that can be detected with a known level of confidence from the dam location that allows for satisfactory prediction of upstream water quality throughout all times of the year. The importance of this work lies in the valuable environmental data that will be collected *year-round* that can be used to discern impacts of controlled and uncontrollable stressors on water quality in this ecosystem. Location of the sensor array in the power dam will allow for changes in water quality to be detected at high resolutions and related to environmental changes being experienced at a broader scale. Full realization of the project outputs will provide water resource managers with the desired ability to more efficiently assess point source compliance with discharge parameters, understand non-point source watershed run off and tributary loading, assess chronic and episodic events such as releases from vessels or combined sewer overflow, as well as identify the impacts of extreme weather events on water quality.

Scope of Work: The goals of this project are to:

I. Maintain year-long continuous high-resolution monitoring of nearshore water quality in the St. Lawrence River through sensor array set up in the Moses-Saunders power dam.
II. Establish the hind-casting capabilities of the hydropower dam sensor arrays.

Large systems such as the Saint Lawrence River require sensors to be placed in reasonable locations. Installing sensor arrays in hydropower dams offers 365 day per year coverage. In comparison, sensors on buoys are limited to ice-free conditions (April to December), suffer from more environmental stresses and potential catastrophic losses (e.g., buoy mooring failure, collisions), damage during deployment and recovery, less opportunity to clean and maintain sensors, and are more expensive and hazardous to deploy and maintain. Sensor arrays installed *in* hydropower dams is an innovative approach to water quality monitoring that has yet to be capitalized.

Location of Continuous Water Quality Monitoring Stations inside a Hydropower Dam: Permission from the New York Power Authority (NYPA) allowed us to install a sensor array at the Moses-Saunders hydropower dam (Upper St. Lawrence River; USLR) using water that flows continuously through the No. 32 generating unit located closest to the US shore. The sensor station in Unit 32 is justified as follows:

i) The St. Lawrence is the only natural outflow of the entire Great Lakes. The dam has an impact on the regional ecology of the river. The US side of the dam is entirely within a USEPA Area of Concern.
ii) Water in the main channel of the river strongly reflects water quality of the head water lake, Lake Ontario. However, since the hydraulic residence time of the USLR is 12 days, it follows that there is appreciable retention of water in slower moving water masses that are characteristic of nearshore zones (Fig. 2). Nearshore locations provide a measure of main channel water mixed with nearshore waters impacted by point sources (e.g., CSO) as well as diffuse sources (e.g., land runoff).
iii) Transects along the nearshore and in the main channel from the Moses-Saunders dam to 40 km upstream indicate that tributary and slack water impacts on river water quality are detectable.
iv) Eel ladders located on units nearest each shore allows continuous water quality monitoring to be related to fish migration behavior.

v) The arrays will not freeze during winter operations since they are located within the dam, unlike sensor arrays deployed on buoys that must be removed during winter. We have demonstrated no effect of temperature in the Moses-Saunders dam on measured water temperature due to high rate of flow through sensor array and insulation of pipes.
vi) The hydropower dam has secure access that provides for well-protected instrument arrays, safe access for personnel, and year-round observations.

Sensor Description and Installation — The following time-stamped water quality parameters are measured at high frequency (0.1 Hz; 1/min): (*i*) water temperature, (*ii*) specific conductivity, (*iii*) turbidity, (*iv*) colored dissolved organic matter (CDOM), (*v*) in vivo chlorophyll-*a* (Chl-*a*), and (*vi*) in vivo phycocyanin (an indicator of potentially toxigenic cyanobacteria). These parameters are measured using two calibrated submersible instruments, a sonde (YSI model 6920 V2-2 for (*i*–*ii*), and a Cyclops 6 (Turner Designs) with Cyclops 7 sondes (*i*, *iii*-*vi*) that are housed in water-tight flow-through chambers bolted to a concrete bulkhead containing water drawn (10 L/min) from high flow stator cooling pipes. Data are collected using an electronic data logger. The C6 is equipped with automatic anti-fouling brushes. Instruments are inspected, cleaned and calibrated every two weeks. At that time, data are downloaded from data loggers. Water samples (1.3 L) are collected to provide voucher samples of size-fractionated Chl-*a*, and ancillary measurements of high interest: nutrients (total phosphorus, dissolved SiO_2 and NO_3^-), major anions (SO_4^{2-}, Cl^-), and phytoplankton community composition using a FluoroProbe in the limnology lab of Twiss.

Upstream (Roving) Sampling for Hind-casting Model Development — Since the greatest scientific value is in the deployment of sensors at established, fixed sites in combination with roving stations, we sampled water quality at discrete upstream locations in July 2014 in order to support hind-casting model development (see Data Analysis and Modeling, below).

Data Analysis and Modeling

Water History Modeling — The high resolution data set collected at the dam will be used to hind-cast upstream water quality. This is the second stage of the project, which we are actively searching for funds to support. In brief, we will be using hydrodynamic modeling to determine the extent of water upstream that is sensed while traversing the hydropower dam sensor arrays. Water currents in the Upper St. Lawrence River are simulated every three hours using the Upper St. Lawrence River Forecasting System (USL, www.glerl.noaa.gov/res/usl), a real-time hydrodynamic model that is part of the Great Lakes Coastal Forecasting System by NOAA. Thus, for any sampling time we can obtain from Dr. Eric Anderson, NOAA-GLERL, environmental data that describes the physical conditions of the river. Using historical data from the time of any given sample collection, we can project the data to provide a time varying depth-averaged representation of the velocity field, which we denote as:

$$\boldsymbol{v} = \boldsymbol{u}(\boldsymbol{x}, t),$$

where $\boldsymbol{v}$ describes the velocity vector at time t at position $\boldsymbol{x}$ in the river (where 2-d vector $\boldsymbol{x}$ gives the position measured in UTM coordinates). Taking a Lagrangian perspective of the flow, we consider individual fluid parcels governed by that velocity field, where we observe the fluid parcel as it moves in time. Taking $\boldsymbol{a}$ to be the position of the fluid particle at time t_0, the position of the particle is given by

$$\boldsymbol{X}(\boldsymbol{a}, t),$$

and its evolution is related to the velocity field by the relationship

$$d\,\frac{\boldsymbol{X}(\boldsymbol{a}, t)}{dt} = \boldsymbol{u}(\boldsymbol{X}(\boldsymbol{a}, t), t), \tag{1}$$

such that the fluid parcel movement is governed by the velocity field. We use numerical integration to solve equation (1), where we also incorporate a stochastic term to account for dispersion of the flow.

***Ensemble of trajectories*:** For a particular sample i, taken at location $\boldsymbol{a}_i$, we choose an ensemble of locations, chosen from a bivariate normal distribution whose centered on the measured sample location. For each point in the ensemble, we can evolve its position backwards in time using the time varying flow field, looking 72 hours into the simulated flow. For each point in the ensemble we determine its velocity at each of those hourly time marks. In other words, for our sample location, we determined (a) where the water had come from over the previous 72 hours, and (b) what the velocity history of each water parcel was. We denote this ensemble of velocity measurements a$\{v_i\}$. This sample is interpreted as describing the distribution of velocity history for the water mass in the vicinity of the sample location. An example of this model output is provided in Figure 2.

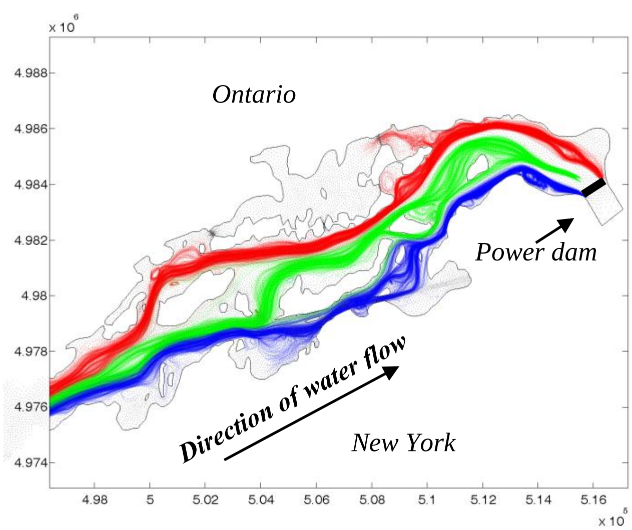


Figure 2. *Water trajectories upstream from the proposed sensor locations at the Moses-Saunders hydropower dam. Red = Canadian Shore (Unit 1), Green = main channel (Unit 17), blue = US shore (Unit 32). Latitude and longitude are UTM coordinates.*

***Modeling and Data Techniques* —** The key enablers with respect to the modeling and analytics aspects of this proposal are taken from three related data analysis approaches: time series analysis, geospatial analysis, and transport dynamics. The Lagrangian model of advection transport, coupled with the velocity information provided by the near-real time USL model allows us to perform a reasonably simple FORWARD calculation using equation (1), which (in principle) would be used to answer the question: "*If you know the water quality in the river at time* T *over region* R*, can you predict the characteristics at some future time at downstream locations?*". Our goal in this project is to invert that problem: "*Given information at a single location, can you predict characteristics over some upstream region at some previous time?*" We use an autosynchronization method to perform estimation and uncertainty propagation on this inverse problem.

From an information theoretic perspective, the time-lag inherent in the physical setting restricts the rate at which information from some upstream events can be transported to the sensor downstream. This information delay dictates that to predict water quality at an upstream location at the *present* time actually involves a two-step process: (1) using present-time sensor data to estimate upstream data at some previous time; and (2) using that first estimate, perform a forward time *prediction* to yield a value for an upstream location at a present time. The first component of that problem requires implementation of delay-synchronization techniques, which remains a cutting edge area of research of which we are fully aware. The forward prediction problem will be tackled via standard techniques for nonlinear time series prediction, where we also have research expertise. For cross-channel prediction, we note that the advection flow model allows the fixed point data stream to provide information about water quality only within a cone with vertex at the sensor location and spreading as we move upstream. Water quality events within that cone would (after temporal delay) be detected by the sensor, while outside that cone, we must use appropriate geospatial techniques to extend the region of prediction. We anticipate that Kriging will provide an appropriate estimator to extend the sensed data and the advection modeled data in the transverse direction.

Model validation for upstream spatial, temporal future, and transverse estimates will be critical to refining the full analytic approach. As such, the roving (upstream discrete) measurements provide critical information. We note that these models are based on Bayesian statistical approaches. As such, although the predicted value results from a maximum likelihood estimate, these computations can also estimate variance. This uncertainty estimate is a critical deliverable of the modeling process. As such, an associated goal of the modeling effort is to provide appropriate scientific visualization via “uncertainty quantification maps” that illustrate our true state of knowledge over both the spatial and temporal regimes. For the model data to be useful for decision making and inference, the “quality” of the predicted values is critical to assessing “risk” of various action plans. Often, the primary output from such models would be an “Expected Value” with a confidence interval around that value. We note that the stochastic nature of the flow dictates that it is most reasonable to think of the water conditions as having a “distribution” of values, represented via prediction intervals. The theory of prediction interval is well developed for both normally distributed and non-parametric data, where we may apply standard statistical techniques.

Project deliverables and status:

This project intends to make a notable contribution to the development of smart infrastructure in the Great Lakes-St. Lawrence River system. Through rational geographic sensor array locations and common data management protocols it seeks to document and communicate to decision makers, in a cost-effective manner, the environmental conditions in the St. Lawrence River.

1. **Deliverable:** High resolution water quality monitoring data set (365 days per year) archived and freely available to users via web-based portals.
    a. **Status:**
        i. **Array:** The array has been operating almost continuously since June 17, 2014. The unit was shut down November 7, 2014 for unexpected maintenance by NYPA of Unit 32 and it was brought back on line in February 2, 2015. The array ran until April 24, 2015. The C6 was sent back to the manufacturer (Turner Designs) for maintenance covered by warranty and will be back on line in the first week of June, 2015. We have resources to maintain basic sensor maintenance and array operations until June 2016.
        ii. **Data:** Data are currently accessible on-line (Google Documents). All data collected are compiled into text files that are available upon request to mtwiss@clarkson.edu. Data will be available via GLOS (see below) in the near future.
2. **Deliverable:** Mathematical modeling tool for establishing hind-casting capabilities of static sensor arrays locations in fluvial systems.
    a. **Status:**
        i. **Modeling:** We have data collected from discrete locations upstream that targeted the main channel and the nearshore, in order to show hind-casting ability to detect Oswegatchie River inflow and its impact on nearshore water quality. More data for extreme events are needed, e.g. high Oswegatchie flow resulting from spring freshet, or extreme weather events such as heavy rains.

Personnel involved with research project

Undergraduate students:

1. Faith Neff (Humboldt State University, 2015), summer NSF-REU participant at Clarkson University
2. Lindsay Avolio (Clarkson University, 2015), research assistant (September – January 2014)

Graduate Student:

1. Anthony Russo (Environmental Science and Engineering program, Master of Science, Clarkson University)

Publications:

1. **Website:** http://www.clarkson.edu/ise/great_rivers1/index.html

1. **Conference Poster Presentations**
    a. Neff, F.C., Sprague, H.M., Skufca, J.D., Twiss, M.R., American Geophysical Union Fall Meeting 2014, "*Water Quality Monitoring of the Upper St Lawrence*

River Using Remote Sensor Arrays Placed in a Hydropower Dam Combined With Hydrodynamic Modeling," American Geophysical Union, San Francisco, CA, (December 8, 2014).

b. Russo, A.D., Neff, F.C., Sprague, H.M., Loftus, S.E., Skufca, J.D., and Twiss, M.R., International Association for Great Lakes Research Annual Meeting, "*Water Quality Monitoring of the Upper St Lawrence River Using Remote Sensor Arrays Placed in a Hydropower Dam Combined With Hydrodynamic Modeling*", International Association for Great Lakes Research, Burlington, VT, (May 26, 2015).

Data Usage

1. **Eel migration:** Data collected during the 2014 eel migration (upstream) season were shared with V. Tremblay, Project Manager-Environment at AECOM (Trois-Rivières QC), the environmental consulting firm under contract with NYPA to operate the eel ladder on the New York side of the Moses-Saunders power dam.
2. **Undergraduate education:** Data collected from June to October 2014 was used as the base of an assignment in Limnology (BY 430 & BY 530) for students to develop skills in data analysis of large data sets related to water quality change as a function of time series.

Collaborations developed

1. **To enhanced capacity:** We have leveraged the opportunity to set up this sensor array to attract other researchers to contribute instrumentation to the array. To date we have acquired a nitrate sensor (optical [UV]; Satlantic) from G.L. Boyer (SUNY-ESF) that we are preparing for installation at Unit 32. At upgraded specific conductivity and temperature probe that includes an optic dissolved oxygen sensor has been included in a FEMRF proposal by J. Farrell (SUNY-ESF) for use at Unit 32.
2. **To increase data availability:** We have been contacted by the Great Lakes Observing System (GLOS) and invited to contribute our data to the GLOS data portal, which is our ultimate objective for data dissemination.
3. **Industrial partnership:** The New York Power Authority is a key partner in this smart infrastructure project. NYPA is committed to participating in scientific study of environmental issues affecting its industry, to regularly measure the environmental performance and share these results with the public, and to incorporate stakeholder and community input for responsible use of the water associated with its projects.

Examples of observations from data collection

Collecting data at one minute intervals provides a rich data set that can be used to relate observations to forcing functions. For demonstration purpose two topics are presented briefly here.

Cyanobacterial blooms: The late summer Cyanobacterial bloom that occurs in the St. Lawrence River was not detectable in 2014 by observations made on the surface but instead by the dispersal of this phytoplankton biomass in the water column (Fig. 3A). Normally, Cyanobacterial blooms are brought to attention by the public who note these scums accumulating on the surface of lakes and rivers and notify authorities responsible, the NYSDEC. Here, we show that the regular Cyanobacterial bloom that occurs in lakes and rivers in our region due to natural forcing functions (such as the grazing resistance Cyanobacterial colony formation) in late summer did occur. We now have a record of this bloom and the nutrients that it consumed (Fig. 3B) and can now compare it with subsequent annual blooms.

Tributary inputs: The Oswegatchie River that flows from the Adirondack Mountains is high in CDOM, compared to the clear waters of the St. Lawrence River that drains Lake Ontario. On July 17, 2014 water was sampled from the nearshore region (2 m isopleth) and the main channel (as defined by hydrodynamic modelling of the river (Fig. 2). CDOM was greater in concentration in the nearshore and lower in the main channel, with instances of high CDOM concentration in the nearshore attributed to low flow by high CDOM-rich tributaries along the shore line (Fig. 4). The flow from the Oswegatchie River and its high CDOM concentration is the dominant input of CDOM into the nearshore region (Fig. 5). However, the high temporal resolution of measurements that are made at Unit 32 shows that other forcing functions such as sunlight strongly influences apparent CDOM concentrations (Fig. 6).

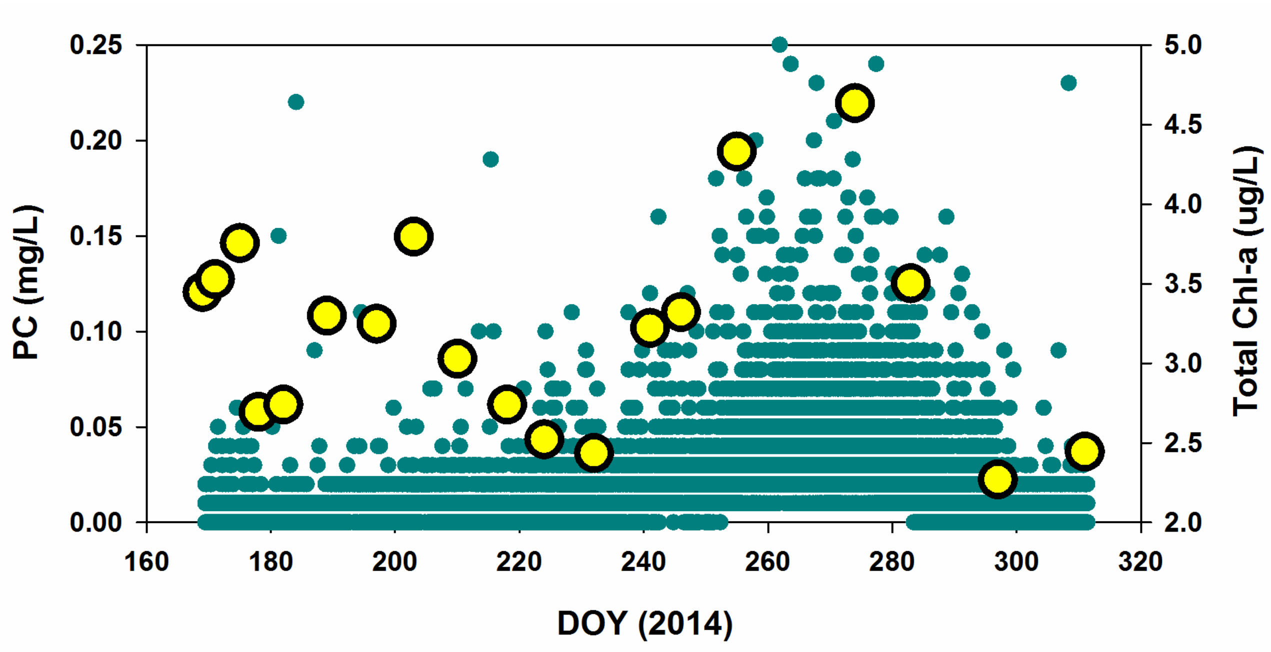
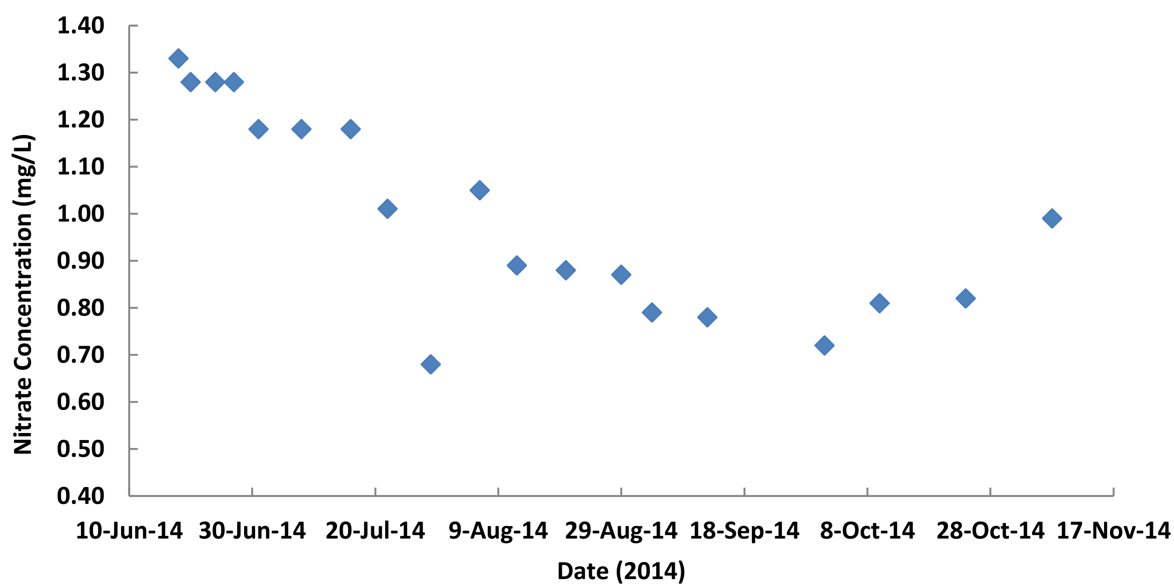


Figure 3A. Cyanobacteria (blue-green algae) increase in late summer 2014 as indicated by phycocyanin (PC) measured in situ and total chlorophyll-a (Chl-a) measured by acetone extracted pigment from grab samples collected at the sensor array in the power dam on days of maintenance and cleaning. **Fig. 3B.** (below) Decrease in dissolved (<0.2 µm) nitrate levels concomitant with the late summer cyanobacterial bloom.



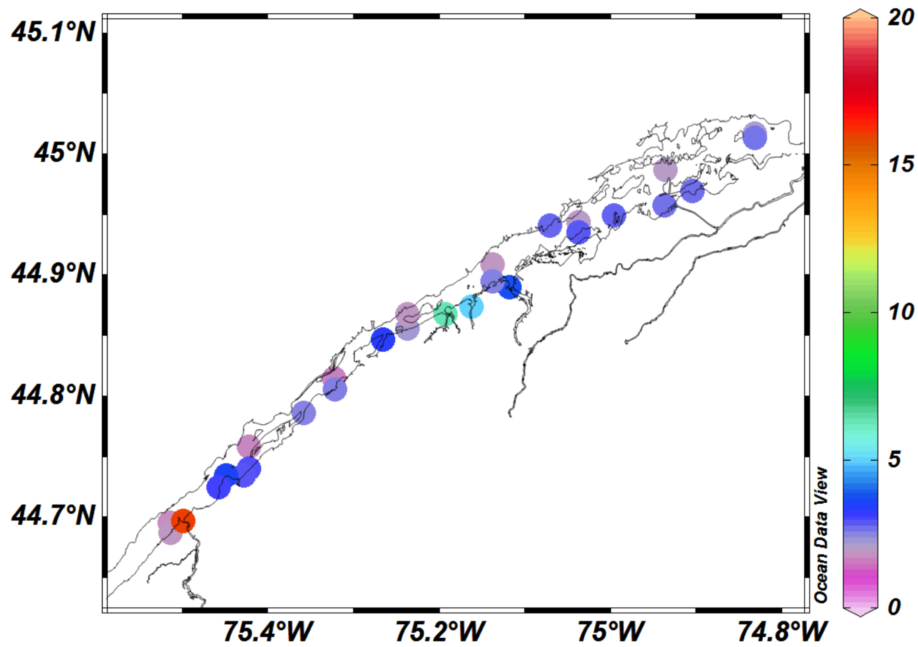


Figure 4. CDOM measured in grab samples collected on 17 July 2014 (DOY 198) from the nearshore (2 m isopleth) and main channel of the Saint Lawrence River from the power dam location (top right) upstream to the Oswegatchie River (lower left).

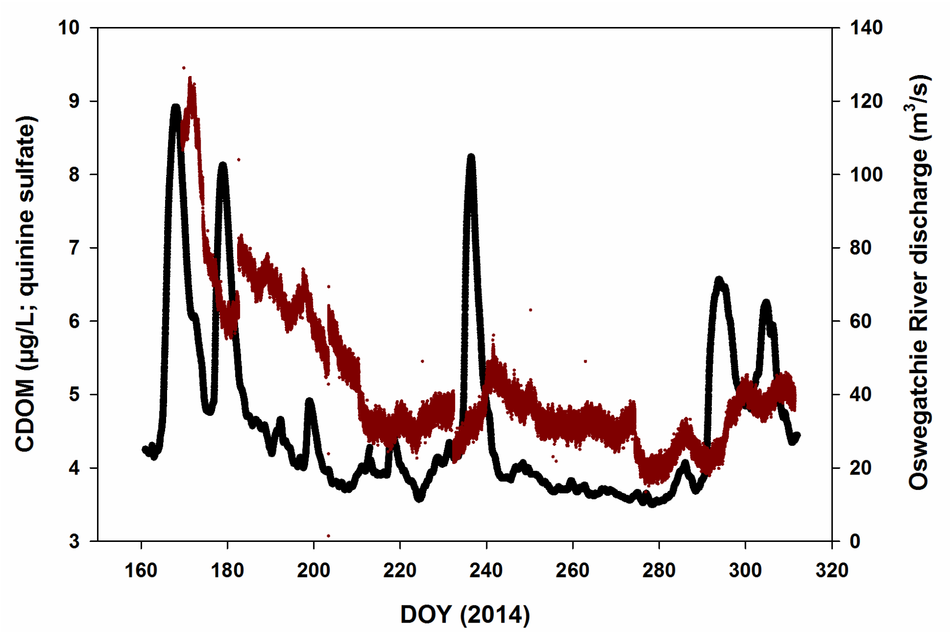


Figure 5. Relationship between discharge (black line) from the Oswegatchie River (high in CDOM) with CDOM measured in the nearshore waters at the Moses-Saunders power dam.

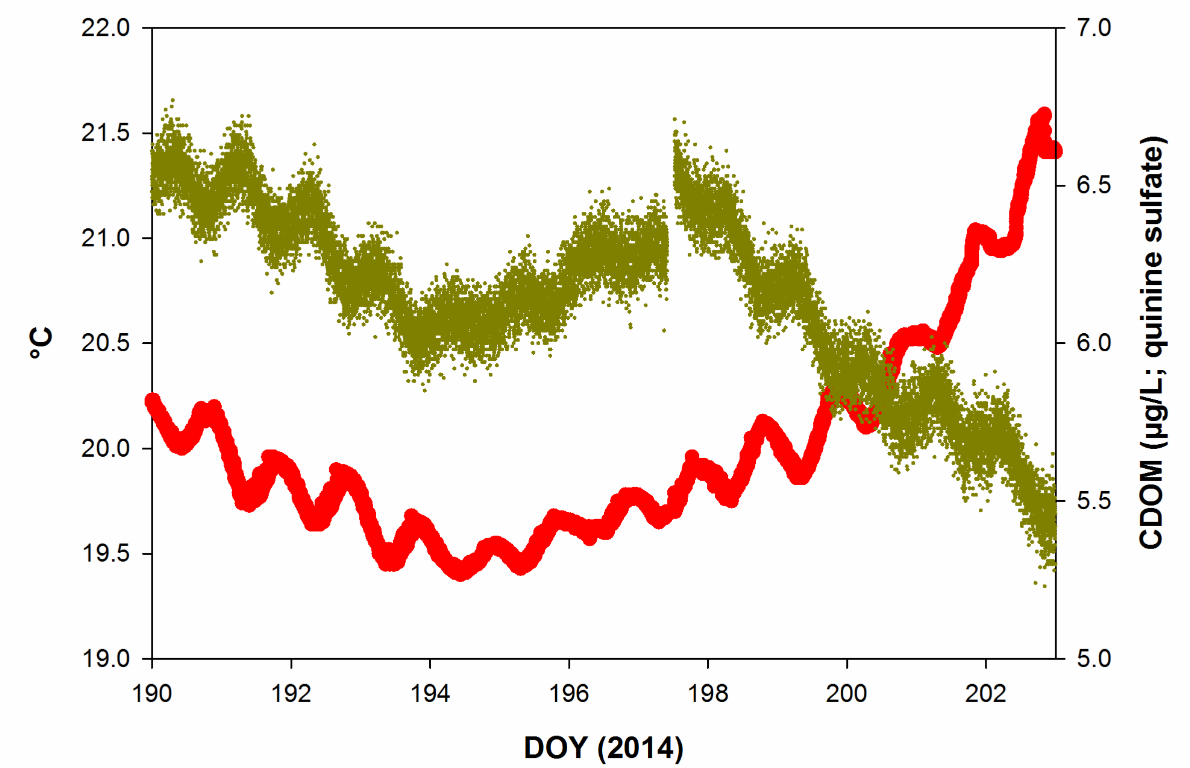


Figure 6. Relationship between daylight and in situ CDOM fluorescence. Water temperature in the nearshore zone is strongly influenced by the time of day, due to slight warming by sunlight in shallow waters (note the daily fluctuations of 0.2 to 0.5 ºC). In contrast, apparent CDOM concentrations decrease during the day, likely due to photobleaching.