Trophic State, Tripton, Pelagic Versus Near-Shore, and Modeling Issues for Cayuga Lake, NY.

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Abstract

An analysis of limnological and input monitoring data for Cayuga Lake, NY is presented that addresses differences in metrics of trophic state and turbidity between pelagic waters and a shallow (< 6 m) near-shore area (the shelf) that receives multiple inputs, within the context of the effects of tripton and mixing processes and modeling needs. The analysis is based on a combination of long-term monitoring and shorter-term studies, including: (1) 10 to 20 years of measurements of concentrations of chlorophyll *a* [Chl], total phosphorus [TP], and other forms of P; (2) 10 years of measurements of Secchi disc depth (SD) and surrogates of light scattering, including turbidity [T_n], and the beam attenuation coefficient at 660 nm [$c(660)$]; (3) P and T_n measurements for point sources and tributaries that enter the shelf (4 to 10 y) and related constituent loading calculations; (4) a 40 site transect along the length of the lake (> 50 km) with rapid profiling instrumentation that resolves spatial patterns in thermal stratification, fluorometric chlorophyll *a*, and $c(660)$; (5) light scattering versus gravimetric features of minerogenic tripton particles from tributary, shelf and pelagic sites; and (6) extent of mixing between the shelf and pelagic waters. Despite the P loading received from local sources, summer average [Chl] levels are not significantly higher on the shelf compared to bounding pelagic waters because of the high flushing rate of the shelf promoted by mixing with pelagic waters. The generally higher [TP], $c(660)$, and T_n, and lower SD on the shelf compared to pelagic waters is shown to reflect inputs of clay minerals. The particle sizes of this material, which diminished SD and increased T_n and $c(660)$ on the shelf, are shown to be in the 1 to 10 μm range. Two water quality modeling initiatives are recommended to guide related management deliberations: (1) a lake-wide seasonal P or nutrient-phytoplankton model, with a two-dimensional transport framework that would provide longitudinal and vertical resolution, and (2)

a shorter-term three-dimensional model for the tripton component of *c*(660) that would simulate the dynamics and spatial details of the impacts of runoff events on clarity levels on the shelf.

Introduction

Cultural eutrophication, most often linked to anthropogenic phosphorus (P) loading, continues to be a concern for many lakes and reservoirs (Cooke et al. 2005). Related manifestations of phytoplankton blooms and poor water clarity represent degradations in water quality that are widely targeted for improvements in rehabilitation programs. However, care must be exercised in considering the common trophic state metrics of concentrations of chlorophyll **a** ([Chl]) and total phosphorus ([TP]), and Secchi disc transparency (SD; Carlson 1977, Rast and Lee 1978, Chapra 1997) in diagnosing such potential problems. In particular, consistent indications from these three metrics can only be expected where phytoplankton biomass is the primary regulator of SD and component of the TP pool (Carlson 1977, Hecky et al. 1993). Substantial quantities of tripton (inanimate particles) cause a disconnect amongst these metrics by making noteworthy contributions to [TP] and decreasing clarity through increased light scattering (Effler et al. 2002b).

Lake and tributary monitoring data support basic limnological characterization, identification of anthropogenic effects and targets for rehabilitation, and the design and testing of mathematical models intended to guide management. Long-term monitoring data sets provide an invaluable perspective to inform management deliberations. Effective integration of this information into contemporary programs, including the total maximum daily load (TMDL) process, is essential for effective management (Lung 2001, Effler et al. 2002a, Gelda and Effler 2003). The need for a TMDL analysis, and the targeted constituents, reflect the failure of a water body to meet specific water quality standards or guidelines. The TMDL is defined as the pollutant loading rate that will result in water quality standards or goals being met; it is the summation of point and non-point contributions, plus a margin of safety intended to account for uncertainties in the quantitative coupling between external loads and in-lake water quality (USEPA 1991). This quantitative coupling takes the form of a water quality model (USEPA 1991).

The water quality model is the central quantitative feature of contemporary management programs, and of TMDL analyses in particular (Lung 2001). For example, the TMDL is determined through iterative *a priori* (Bierman and Dolan 1986) model projections that establish the external loading levels that will result in meeting in-lake goals or standards. A credible and representative model for this process is one that represents a synthesis of the understanding of the system and the behavior of the constituents of interest. The structure and capabilities of such models need to reflect: (1) the behavior of the target constituent(s); (2) the magnitude(s) and format(s) of the water quality goal(s) or standard(s); (3) the range of management alternatives being considered; and (4) results of related system-specific monitoring and process studies. Structural needs of water quality models can generally be partitioned according to transport and kinetic submodels (Chapra 1997). The primary issue for transport submodels is the physical dimensionality (e.g., one-vertical, two- vertical and longitudinal, and three- vertical, longitudinal, and lateral) necessary to describe the important spatial features of impact and regulating transport processes (Martin and McCutcheon 1999). The water quality issue(s) largely drives the state variables of the kinetic submodel (the limnological features to be predicted) and influences importantly its structural needs, though widely different levels of complexity are available for certain issues (Chapra 1997). Moreover, different water quality issues may have widely divergent time scales of interest, such as short-term concerns for turbidity impacts from runoff events or the longer seasonal focus for levels of phytoplankton biomass (Thomann and Mueller 1987). Differences in water quality between pelagic and shallower near-shore areas are influenced by local hydrologic and material loading and bathymetric conditions, as well as by an array of mixing processes (Martin and McCutcheon 1999). These spatial differences are of broad management concern and offer special challenges for effective structuring of models to represent these conditions and associated drivers.

Here we analyze long-term limnological and tributary monitoring data for Cayuga Lake, NY, in the context of water quality issues related to cultural eutrophication and clarity, the effects of tripton and transport processes, the needs for the development and testing of a water quality model(s), and the appropriate target constituent(s) for a TMDL analysis. Differences between near-shore and pelagic regions are documented and considered with respect to origins and structural needs of the model(s) and the role of tripton. This case study is valuable because of the broad concern for the features of water quality considered, the complications from tripton, and the issue of pelagic versus shallow zone differences.

Cayuga Lake and Water Quality Issues

Cayuga Lake (lat. 42° 41.3′ N; long. 76° 41.2′ W) is the fourth easternmost of the New York Finger Lakes (Fig. 1). This lake is narrow and configured along a north/south axis (Fig. 1). It has the second largest volume (9.38 x 10^9 m^3) and the largest surface area of the Finger Lakes (Schaffner and Oglesby 1978). The mean and maximum depths are 54.5 and 132.6 m, respectively. This alkaline hardwater lake has a warm monomictic stratification regime, stratifying strongly in summer, but only rarely developing complete ice cover (Oglesby 1978). The lake's hypolimnion remains well oxygenated (Oglesby 1978). Water exits the basin through a single outlet at the northern end. The average detention time of the lake is about 10 years (Shaffner and Oglesby 1978, Michel and Kraemer 1995). About 40% of the tributary inflow is contributed by Fall Creek and Cayuga Inlet that enter at the southern end (Fig. 1). Parts of the shallow southern end of the lake had been bordered by a marsh before it was filled in the early 1900s to support development. Phytoplankton growth in the lake is P limited (Oglesby 1978). Zebra mussels invaded this lake and other waters of the region in the early to mid- 1990s (Effler and Siegfried 1994, New York Sea Grant 2000).

Cayuga Lake is an invaluable resource to the region that is used for contact recreation, fishing, navigation, as a water supply by several communities, and for disposal of treated municipal wastewater. The largest adjoining community is the City of Ithaca (population ~30,000) that is located at the southeastern corner of the lake. The shallow southern end of the lake receives three permitted discharges, effluent from two domestic wastewater treatment facilities (Ithaca Area WWTP, and Cayuga Heights WWTP), with average discharge flows of 0.3 and 0.07 m^3/s, and spent cooling water from a "lake source cooling" (LSC) facility (Cornell University; Fig. 1). The limit for the concentration of total phosphorus ([TP]) of the WWTP effluents had been 1 mg/L (Great Lakes basin standard). Substantial reductions in P loading from the Ithaca Area WWTP have been achieved recently from upgrades in treatment. Cold water is withdrawn from a depth of nearly 80 m (hypolimnion) by the LSC facility and returned to the shallow waters of the southern end of the lake. The discharge varies seasonally, from ~0.65 m^3/s in the cold months to ~2 m^3/s in summer. This represents an artificial form of internal cycling (e.g., load) of P.

Conditions in the shallow southern end of the lake have generally been considered degraded relative to the pelagic zone (Oglesby 1978). This shallow southern zone, demarcated as the southernmost 2 km where depths are less than 6 m (Fig. 1), is designated here as the "shelf". The shelf is on New York's list of water quality limited systems (section 303d of the Clean Water Act). The "causes/pollutants" designated by the state regulatory agency for the impairment of conditions on the shelf are “phosphorus, silt/sediment, and pathogens”; the identified sources were both municipal and non-point inputs. A TMDL analysis(es) is anticipated.

Some interpretation of meaning and appropriate metrics for the listed causes/pollutants is valuable to bring focus to the analysis presented in this paper. Phosphorus is a stated concern here as a central driver of cultural eutrophication and the commonly associated attributes of high concentrations of phytoplankton biomass ([Chl]) and low Secchi disc transparency (SD). The silt/sediment designation refers to inanimate particles, tripton in the language of limnology (Wetzel 2001), and would commonly be represented by the metrics of the concentration of total suspended solids ([TSS]) or turbidity (T_n). The closure of the public swimming beach located on the southern portion of the shelf in the early 1960s was attributed to both turbidity and public health (high concentrations of indicator bacteria) problems.

The “pathogens” listing on the 303d list is ambiguous as it potentially includes broad ranges of microbes of public health concern, with widely different analytical and model framework demands. Pathogenic protozoans, particularly *Giardia* and *Cryptosporidium*, are particularly problematic because of the extraordinary monitoring and measurement demands and the required “particle tracking” modeling approach (Dimou and Adams 1993, Costa and Ferreira 2000). Modeling of the fecal coliform indicator group is a more tractable approach that has been applied with some success where defined tributary inputs have imparted conspicuous signatures in time and space in receiving waters (Canale et al. 1993, Hyer and Moyer 2004). However, available data (Cayuga Lake Watershed Network 2007) are not adequate to support development and testing of a fecal coliform model, thus, the pathogen issue is not considered further here. In addition, anecdotal observations suggest proliferation of submerged macrophytes and macroalgae on the shelf. An increased zebra mussel population may be promoting these conditions (Hecky et al. 2004, Auer et al. 2008).

Methods

Lake data for this analysis were drawn from a number of monitoring efforts conducted since the late 1960s. Chlorophyll **a** and [TP] data from before the 1990s are representative of pelagic areas (limited to [TP] and [Chl]); thereafter observations from the shelf were also available. The most spatially and temporally comprehensive data for the common metrics of trophic state were collected for the shelf and adjoining areas as part of an on-going program (ten years of data considered here) to assess potential impacts of Cornell University's LSC facility (operations initiated in 2000) on the lake, conducted by the authors and coworkers. Certain data for two years (1998 and 1999) of this program have been presented previously (Matthews et al. 2002).

Five sites monitored as part of the LSC program are used here to represent conditions on the shelf (1a, 1b, 3, 4 and 5; Fig. 1). Pelagic conditions are represented here primarily by a single site (8) located ~ 13 km north of the southern end of the lake (Fig. 1). All of these sites have been sampled bi-weekly over the April – October interval. Composite (depth) samples from the epilimnion, formed from equal volumes of sub-samples from depths of 0, 2 and 4 m, are collected at sites 5, and 8; those for the other shallower sites were formed from sub-samples from 0 and 2 m. The influent to the LSC facility is monitored weekly. Laboratory analyses included [TP], total dissolved P ([TDP]), soluble reactive P ([SRP]), and turbidity (T_n), all measured according to standard methods (Clesari et al. 1998), and [Chl] (according to Parsons et al. 1984). Field measurements at each of the sites included temperature (T), and the beam attenuation coefficient at 660 nm [*c*(660)]. These measurements were made by sensors configured in a steel cage and powered by a Sea Bird® Sealogger Profiler. Both *c*(660) (Babin et al. 2003, Loisel et al. 2007) and T_n (Kirk 1994, Effler et al. 2006) are accepted surrogate measures of the light scattering coefficient (*b*) that quantifies the intensity of the light scattering process. A strong linear relationship(s) generally prevails between *c*(660) and T_n [e.g., $T_n = 2.3 \times c(660)$; Effler et al. 2006].

A single longitudinal transect of SeaBird profiles (n = 40 sites) was collected along the entire length of Cayuga Lake on August 6 1996; these profiles also included the measurement of chlorophyll **a** fluorescence [Chl_f]. Hourly measurements of T were made at a depth of 1 m at a fixed location on the shelf (Fig. 1) over the April – October interval annually as part of the LSC monitoring program. The LSC withdrawal (influent), is monitored weekly for [SRP]. Fall Creek and Cayuga Inlet were monitored for [TP], [TDP], [SRP] and T_n bi-weekly (on the day of lake monitoring) near their mouths over the 2003-2006 period.

Estimates of TP loading from the various inputs to the shelf were supported by continuous measurements of flow rate in Fall Creek (USGS gage no. 04234000), Cayuga Inlet (USGS gage no. 04233000), and the discharge of the two WWTPs and the LSC facility, and discrete measurements of [TP] (twice per week for Ithaca Area WWTP, and weekly for Cayuga Heights WWTP and LSC discharge). Phosphorus data from the WWTPs are those reported by the facilities. Additional data for Fall Creek for selected high flow intervals over 2003-2006 were provided by the Community Science Institute. Loads of TP from the WWTP discharges were calculated at a monthly time step as the products of monthly average flows and concentrations. Loads from the two large tributaries were calculated at a daily time step with the FLUX software (option 6, log transformed concentration-flow relationship), designed for such applications (Walker 1995).

The light scattering characteristics of individual minerogenic (inorganic) particles, including projected particle area, particle size, and elemental composition, were measured by an individual particle analysis (IPA) technique, Scanning electron microscopy interfaced with Automated X-ray microanalysis and image analysis (SAX; Peng and Effler 2005). Six samples were analyzed, two each from Fall Creek, site 5 (shelf), and site 8 (pelagic). One sample represented higher turbidity and runoff conditions, the other corresponded to low flow conditions. SAX provides both morphometric and chemical characterizations of individual particles. Inorganic particles were chemically classified into one of five classes, `Clay´ (clay minerals),`Quartz´, `Calcium-rich´ ($CaCO_3$), 'Calium-agg' (aggregate particles – that include partial coating with $CaCO_3$), and `Other´ (miscellaneous) (e.g., Peng and Effler 2005). Analytical protocols for SAX have been described previously (Peng and Effler 2005, 2007). SAX results are presented in three formats, the minerogenic particle projected area per unit volume of water (PAV_m), the minerogenic scattering coefficient at 600 nm [$b_m(660)$] (calculated according to Mie theory; Peng and Effler 2007), and minerogenic particle volume per unit volume of water (VV_m). Particle projected area and light scattering are fundamentally (and nearly linearly) linked (Stramski et al. 2001, Peng and Effler 2007). Accordingly, measurements of PAV_m and calculated values of b_m, have been reported to be tightly coupled (Peng and Effler 2007, Peng et al. 2007). Values of VV_m are presented as a metric of gravimetric concentrations, as it is approximately proportional to a mass concentration for particle types with similar specific gravities. Values of b_m, and VV_m are presented in cumulative particle size contribution formats, to resolve the contributions of different particle sizes to these metrics (Babin et al. 2003, Peng and Effler 2007).

Results and Discussion

Loads to the Shelf

Substantial interannual variations in hydrologic and estimated P loading to the shelf occurred over the 10 y interval 1998 – 2007 (Fig. 2a – c). Systematic interventions associated with the discharges contributed to these variations. The average inflow rate to the shelf for the April – October interval increased approximately 11% following the startup of the LSC facility in 2000 (Fig. 2a). The inflow rates from the two WWTP discharges have been relatively uniform, particularly compared to natural variations in runoff from the two large tributaries. Moreover, these discharges make small contributions to the total inflow to the shelf; e.g., together these inputs represented on average 6% of the inflow. Inputs from Fall Creek and Cayuga Inlet dominate overall inflow to the southern end of the lake. Accordingly, the wide interannual variations in the overall inflow to the shelf have been driven primarily by natural variations in runoff from these tributaries. Average tributary flow ranged from about 2 m^3/s in 1999 to 14 m^3/s in 2004. Flow rates from these two tributaries are similar and temporal patterns generally track each other; e.g., the rates have been highly correlated ($r = 0.90$) at a monthly time step. The flow from Cayuga Inlet is about 85% of that observed from Fall Creek. The effects of a wide range of tributary flows have been captured in the last 10 y of monitoring. The average April – October flows in Fall Creek for 1999 and 2004 were ranked the 3rd lowest and 2nd highest of the 83 y record, respectively.

Estimates of P loading were partitioned according to the dissolved (TDP_L, kg/d) and particulate (PP_L, kg/d) fractions, in recognition of the widely different levels of bioavailability of these forms to support algae growth (Young et al. 1982, Auer et al. 1998, Effler et al. 2002). Most (Young et al. 1982), if not all (Auer et al. 1998), of the dissolved pool is either immediately, or subsequent to enzymatic hydrolysis (Gage and Gorham 1985), available. In sharp contrast, the portion of the PP_L that becomes available (e.g., converted to dissolved forms) is substantially less, though municipal waste constituents are generally more available than terrigenous material (DePinto et al. 1981, Young et al. 1982, Effler et al. 2002a). The fraction of PP_L available from most tributaries is between 30 and 50%, while values for WWTPs are typically > 60%.

The P loadings from the WWTPs were assumed to be split evenly between the dissolved and particulate pools, as observed for another local facility with similar P treatment (Effler et al. 2002a). The partitioning for the LSC input was based on measurements made in the lake (hypolimnion) adjoining the intake. The concentration of SRP in the hypolimnion withdrawn by the LSC facility increased over the 2000 to 2006 interval from ~ 5 to ~ 9 µg/L on average (modest annual seasonality embedded; Fig. 3a). Accordingly, this has shifted the LSC load of this available form higher. Such an increase in hypolimnetic concentrations is likely reflective of lake-wide metabolism (e.g., shift in mineralization of depositing organic material), given the active mixing throughout those layers mediated through internal waves. Tributary loading estimates of these fractions were based on stream-specific concentration versus flow relationships developed from the monitoring observations (Fig. 3b and c). Increases in concentrations of both fractions were observed at higher flows, though the relationship was stronger for PP (Fig. 3b) compared to TDP (Fig. 3c). Concentrations of TDP were generally somewhat higher in Fall Creek than Cayuga Inlet. The FLUX software supports estimates of uncertainty for the tributary loading calculations. Coefficients of variation (CV) for the Fall Creek estimates of PP_L and TDP_L for the 1998-2006 interval were 33 and 6%, respectively; for Cayuga Inlet the CVs were 26 and 40%.

The large interannual variations in both TDP_L (Fig. 2b) and PP_L (Fig. 2c) were primarily driven by the dynamics of stream flow (Fig. 2a). However, embedded within these dynamics were systematic decreases in loading from the WWTPs from improved treatment, particularly at the Ithaca Area facility. These improvements for this facility were manifested in two steps, a 1.5-fold decrease for the 2002 – 2005 interval relative to 1998 – 2001, and a 3.7-fold decrease in 2006 and 2007 from the 1998-2001 interval. These effects on overall PP_L were modest because the tributaries often made much greater contributions (Fig. 2c). The PP_L represented approximately 67% of the P loading to the shelf over the 10 year period. The reductions in loading from the WWTPs were relatively more noteworthy for the TDP_L. These point source inputs represented the majority of the loading of this bioavailable fraction in the earlier portion of this period, particularly in the low runoff years of 1999 and 2001. However, increased contributions from the tributaries in high runoff years, such as 2004 and 2006, can mask the benefits of the major reductions in loading from the point sources (Fig. 2b). The contribution of the LSC discharge has generally been relatively minor. However, under low flow conditions and following the upgrades in treatment at the WWTPs, such as prevailed in 2007, LSC represented about 7.5% of the P loading to the shelf.

The flow-weighted [TP] for the mixture of the various inputs (three discharges and two tributaries , $[TP]_{fw}$) is a valuable diagnostic that integrates the effects of flow and loads from the multiple inputs, according to

$$[TP]_{fw} = TP_L \div Q \qquad (1)$$

where $TP_L = TDP_L + PP_L$. High concentration inputs thus have a disproportionate effect on $[TP]_{fw}$ relative to their contribution to total flow. If the shelf was isolated from the remainder of the lake (e.g., with a controlled outflow to the main lake) [TP] concentrations on the shelf would be expected to approach $[TP]_{fw}$. Calculated values of $[TP]_{fw}$ ranged from ~ 45 μg/L in 2007 to ~ 120 μg/L in 1998 (Fig. 2d). Largely progressive decreases in the dissolved component were calculated over the 2001 to 2007 interval (Fig. 2d). The particularly low $[TP]_{fw}$ value for 2007 reflects the combined effects of low Q and increased treatment at the Ithaca Area WWTP.

Turbidity levels in the two tributaries increase at higher levels of runoff, in a manner similar to that observed for PP (Fig. 3b and d). Significant ($p < 0.0001$) positive relationships prevailed between PP and T_n (Fig. 3e), linking the P content and light scattering attributes of these terrigenous particles. The particles in Fall Creek were significantly (one-tailed t-test, $p < 0.0001$) more enriched with P than in Cayuga Inlet; the average PP ÷ T_n ratios were 4.9 and 3.1, respectively.

Limnological Characterization

Trophic State

Long-term conditions and interactions are reviewed here for the three common trophic state indicators, [Chl], [TP], and SD, for pelagic waters and the shelf (Fig.4a - c). Summer (June – August) average values for the upper waters are considered in the review of long-term trends, to be consistent with the constructs of the TP "guidance" value (i.e., open to some regulatory discretion) for New York to protect recreational uses of lakes (NYSDEC 1993). This limit, 20 μg/L as a summer average for the upper waters, is generally consistent with the upper bound of mesotrophy specified for [TP] by several researchers (Vollenwider 1975, 1982, Chapra and Dobson 1981, Auer et al. 1986). Monitoring coverage for [Chl] and [TP] included the mid-1960s to late 1970s and regularly since the mid-1990s; SD data and observations for the shelf (represented by average values) are available only for this last interval (Fig. 4).

*Chlorophyll **a** Concentration [Chl]*

Summer average [Chl] increased from the late 1960s to the 1970s but has been lower since the mid-1990s (Fig. 4a). The indicated lower levels of phytoplankton biomass over this interval (all within mesotrophic limits, Chapra 1997) may reflect the effect of various drivers, including New York's continuing ban on high P detergents (since the early 1970s), improved municipal wastewater treatment and invasion of the zebra mussel (New York Sea Grant 2000). Note that no systematic decrease has yet occurred in [Chl] in response to the recent reduction in P loading from the Ithaca Area WWTP. In 2006 the somewhat higher [Chl] could have been due to the more than compensating increases in tributary inputs from elevated runoff (Fig. 2b and c). However, the average [Chl] values for the shelf and pelagic site in 2007 (Fig. 4a) remained similar to observations in recent years, despite the substantial decreases in both TDP_L (Fig. 2b) and PP_L (Fig. 2c). The mean summer [Chl] on the shelf for the 1994 – 1996 interval was 70% higher than in pelagic waters. However, based on measurements made by the authors and co-workers over the 1998 – 2007 interval (Fig. 4a), the summer mean values for the shelf and pelagic waters (site 8) were not significantly different. Despite loadings received from major local sources of P (Fig. 1), there is no compelling evidence that it causes conspicuously higher levels of phytoplankton biomass on the shelf relative to bounding pelagic waters, as represented by site 8.

Interannual variations in the mean [Chl] have not been significantly correlated with those for [TP] or SD, on the shelf or at site 8. Moreover, [Chl] levels at this pelagic site were independent of interannual differences in P loading to the shelf. However, a significant ($p = 0.004$) positive relationship was observed for summer average [Chl] on the shelf; 67% of the interannual variability was explained by differences in TDP_L (Fig. 4d). With the exception of lower concentrations in April, there has been no strong recurring seasonality in [Chl] in the lake over the April-October interval (Fig. 4e).

Phosphorus Concentrations

Decreases in [TP] in pelagic waters from the early 1970s to the last 10 y interval were modest compared to those reported for [Chl] (Fig. 4a and b). Noteworthy differences in [TP] levels between the shelf and the pelagic site were a recurring feature over the 1998 - 2007 period (Fig. 4b). Summer average [TP] exceeded the guidance value in pelagic waters in only two (1968 and 1994) of the eighteen years of the record. However, this threshold was exceeded in eight of the thirteen years of monitoring of the shelf, a condition that doubtless was a primary driver for the 303d listing and designation of P as a “cause/pollutant”. Multiple lines of evidence indicate that [TP] levels are higher on the shelf than in pelagic waters because of higher non-phytoplankton particle (e.g., tripton) contributions of P, received primarily in the form of particulate P (PP) from stream inputs. PP is the dominant form of P in the lake’s upper waters representing > 65% on the shelf and at site 8, on average.

Runoff events (e.g., Fig. 5a) cause local enrichment of forms of P, particularly PP (Fig. 5b and c), and turbidity (Fig. 5d) on the shelf that diverge strongly from lower levels maintained in pelagic waters. This is illustrated here for the late June to early October interval of 2004 that bounded a period of particularly high tributary flow with a number of runoff events (Fig. 5). Convergence of conditions on the shelf and the pelagic site with respect to P concentrations, [Chl], and T_n was indicated before (through June) and after (October) the high runoff interval. Dramatic enrichments in [PP] (Fig. 5b) and T_n (Fig. 5d), with noteworthy increases in [TDP] (Fig. 5c), were observed on the shelf from the runoff events. Moreover, substantial spatial heterogeneity was commonly manifested for particulate-based metrics on the shelf (± 1 standard deviation bars of Fig. 5) during these intervals indicating the associated short-term loads were not evenly distributed throughout the shelf. An example of this heterogeneity is illustrated in an aerial photograph of the southern end of the lake following a runoff event (Fig. 6). The response of [Chl] to these increases in hydrologic and nutrient loading was modulated by comparison (Fig. 5e), with much smaller shelf versus pelagic zone differences relative to those observed for [PP] (and [TP]) and T_n. Somewhat higher average [Chl] values were observed in August on the shelf, with substantial spatial heterogeneity (Fig. 5c). However, higher concentrations were observed at the pelagic site in mid-July, late September and early October.

The ratio [PP] ÷ [Chl] is adopted here as a metric of the consistency of [PP] (and [TP]) levels with attendant phytoplankton biomass levels. The distribution of the ratio [PP] ÷ [Chl] has been shifted higher for the shelf sites compared to the pelagic site (Fig.7a and b); the median for the shelf (3.2) was approximately 1.7 - fold higher than for this pelagic location. These ratio values exceeded the range commonly attributed to plankton (0.5 – 1.0; Bowie et al. 1985, Chapra 1997) at site 8 for about 93% of the observations, indicating noteworthy tripton contributions even at the pelagic site. Particularly high ratio values occur on the shelf from runoff events, as illustrated for 2004 (e.g., Fig. 5b and e). The higher shelf ratios indicate greater tripton contributions in these near-shore areas compared to the pelagic site. Clay minerals, that dominate the turbidity load received from the tributaries (subsequently), and usually tripton levels on the shelf and in the lake's pelagic waters (Effler et al. 2002b), are known to often be enriched with P (Kuo and Lotse 1972, Martin and Gloss 1980).

The effects of terrigenous tripton-based PP inputs in driving [TP] differences between the shelf and pelagic waters is also manifested in positive relationships with runoff. The residuals of individual paired measurements of the shelf average [TP] ($[TP]_s$) and the pelagic site [TP]

($[TP]_p$) have been significantly ($p < 0.0001$) positively correlated ($r = 0.54$) with tributary flow (Fig. 7c).

Light Scattering and Secchi Disc

A strong relationship between SD^{-1} and $c(660)$ prevails in Cayuga Lake (Fig. 8a), establishing that light scattering particles, rather than light absorbing processes, regulate clarity in the lake (e.g., Davies-Colley et al. 1993). Moreover, it establishes a coupling between SD, often perceived as a trophic state metric, and the turbidity issue. Further it supports the use of $c(660)$ as a surrogate metric for the optical attribute of clarity on the shelf, necessary for certain sites and intervals when $SD \geq$ depth. Summer average SD values at site 8 were systematically higher than those on the shelf throughout the 1998-2007 period (Fig. 4c), 1.3-fold on average. Multiple lines of evidence support the position that these spatial patterns, as well as temporal features, of light scattering and clarity in the lake are regulated more by tripton than phytoplankton biomass.

Phytoplankton biomass, as represented by [Chl], was not a significant regulator of the dynamics of $c(660)$ on the shelf (Fig. 8b), and explained only a modest percentage (~ 25%) of the variations observed at site 8 (Fig. 8c). Minerogenic particles, particularly clay mineral particles, have instead been reported to be the primary driver of variations in $c(660)$ and SD on the shelf as well as in pelagic areas (Effler et al. 2002b, Peng and Effler 2005). Moreover, numerous measurements of $c(660)$, particularly for the shelf (Fig. 8d and e), have been higher than can reasonably be expected for the attendant phytoplankton biomass, as indicated by the paired measurements of [Chl]. The [Chl]-based estimates presented here utilized a modified version [in terms of $c(660)$ instead of $b(\lambda)$] of the empirical relationship developed between b and [Chl] in marine waters by Morel and Maritorena (2001)

$$c(660)_{\mathrm{Chl}} = 0.354[\mathrm{Chl}]^{0.766} \tag{2}$$

where $c(660)_{\mathrm{Chl}}$ is the estimated contribution of phytoplankton to $c(660)$. Values of the ratio $c(660) \div c(660)_{\mathrm{Chl}}$, based on paired measurements of $c(660)$ and [Chl] were frequently > 1, consistent with contributions from tripton. The population of values was shifted higher for the shelf compared to the pelagic site (Fig. 8d and e), consistent with the local effects from tripton inputs from the tributaries.

Interannual variations in SD (as SD^{-1}) have been strongly correlated with those for [TP] for both the shelf ($r = 0.89$, $p = 0.00014$) and the pelagic site ($r = 0.7$, $p = 0.036$; Fig. 8f). The much higher slope of the linear least squares regression fit for the shelf reflects the greater interannual variations in both of these metrics in this area of the lake. This feature is consistent with a greater susceptibility of the near-shore area of the shelf to variations in tripton inputs, particularly from the tributaries. Moreover, these dependencies, in concert with the lack of significant relationships between [Chl] and either of these metrics, are consistent with a shared dependency of SD and [TP] on tripton in this lake. A manifestation of the regulation of spatial differences of both [TP] and $c(660)$ by differences in tripton levels is the positive relationship between the residuals of $c(660)$ [$\Delta c(660)$] and [TP] (Δ[TP]) formed from the paired shelf (average) and pelagic observations (Fig. 8g). The higher residuals reflect the short-term local effects of tripton on the shelf following runoff events (e.g., Fig. 5b, c and d). This relationship represents a modeling opportunity, as simulation of spatial differences in one metric effectively could support predictions of the other.

SAX results provide insights on the minerogenic component of tripton (the dominant fraction; Effler et al. 2002b) in Fall Creek, on the shelf, and in pelagic waters (Fig. 9, Table 1). The minerogenic light scattering (b_{m}) in this tributary, like many others (Peng et al. 2004), is dominated by clay minerals, with quartz being the second largest contributor, over a wide range of runoff (Table 1). This "terrigenous origins" signature was preserved on the shelf and at the pelagic site for the June 30, 2004 samples, when T_n and b_m levels were low (Table 1). The terrigenous signature was modified in the lake for the July 29, 2004 samples by $CaCO_3$ precipitation (Table 1), a component of the minerogenic tripton of this system that has an autochthonous origin. This phenomenon ("whiting") is common in hardwater alkaline lakes of this region, making noteworthy contributions to background b_m levels over short intervals (e.g., 2 to 4 weeks), but with substantial interannual variations in intensity (Effler 1996). However, the whiting component of b_m remains substantially less than the elevated terrigenous component that occurs on the shelf from runoff events (Upstate Freshwater Institute, unpublished data). The SAX-based estimates of b_m explained nearly all of the variability in the paired T_n values for the samples analyzed here, even when the very high values from Fall Creek on July 29 were eliminated (Table 1; $r^2 = 0.97$, $p < 0.002$, $n = 5$). This is consistent with the central role of minerogenic tripton in regulating turbidity and clarity in this tributary and the lake.

The relative contributions of different particle size classes to overall b_m is shown for the late July samples in a cumulative format (Fig. 9a). More than 90% of b_m for all three of these samples, as well as those from the June sampling, were associated with particles in the size range of 1 to 10 µm. The median value (d_{50}, Fig. 9) in these cumulative patterns is valuable in describing the relative importance of different particle sizes in this range. The d_{50} values for b_m were within the range 2.26 to 4.89 µm. The particle size dependency of VV_m ($d_{50} - VV_m$) is shifted systematically toward larger sizes for the minerogenic tripton of this system (Fig. 9b, Table 1), as observed elsewhere (Effler et al. 2008). These systematic differences, delineated through the SAX characterizations, provide system-specific evidence for the disconnect in the portions of the particle population represented by surrogate metrics of light scattering [T_n or *c*(660), Fig. 9a] versus gravimetric (Fig. 9b) measurements. This disconnect is an important factor contributing to the widely reported variance in empirical [TSS] – T_n relationships (Davies-Colley and Smith 2001).

Hydrodynamic/Transport Issues and a Lake-Wide Survey

Hydrodynamic mixing processes, driven by the wind, including circulation currents and internal waves, promote the flushing of the shelf and transport of local inputs into the pelagic zone. The rate of flushing of the shelf is apparently rapid enough relative to the effective growth rate of phytoplankton to prevent recurring gradients in phytoplankton biomass between the shelf and the pelagic site (Fig. 4a), despite the localized inputs of P (Fig. 2d). A clear manifestation of this effect is the substantially lower shelf [TP] levels (Fig. 4b) observed relative to the volume weighted concentrations of the inflows received from the local inputs (Fig. 2d).

A dynamic mass balance analysis was conducted for TP on the shelf to provide a rough estimate of the effective flushing rate of this shallow area, which accommodates the effect of mixing with pelagic waters. The shelf is treated as a completely mixed reactor that is hydrodynamically coupled to pelagic waters by an effective bulk transport coefficient E′ (m^3/s), and conservative behavior of TP is assumed. Accordingly,

$$V\frac{d[TP]_s}{dt} = TP_L - Q\cdot[TP]_s + E'([TP]_p - [TP]_s) \qquad (3)$$

where V is the shelf volume ($8 \times 10^6 m^3$ for 6 m depth boundary, Fig. 1), and Q is the sum of local inflows. The model is mechanistically crude, uncertainties in inputs (e.g., loads) exist, and some non-conservative behavior in TP probably occurs (e.g., short-term deposition/resuspension cycling). Despite these limitations, the analysis serves to provide a reasonable first estimate of the extent of mixing between pelagic waters and the shelf. Two flushing rates are presented for a selected year (2001) to illustrate the effect of mixing with pelagic waters. The first (fr1) corresponds to a hypothetical plug flow set of conditions, with no mixing effects with pelagic waters

$$\mathrm{fr1} = Q \div V \tag{4}$$

The second (fr2), systematically higher, rate includes the effects of mixing with pelagic waters, according to

$$\mathrm{fr2} = (Q + E') \div V \tag{5}$$

The value of E' was determined through application of the dynamic mass balance.

The time series presented for fr1 (Fig. 10a) has a daily time step, consistent with that of the inflow data. The time series of fr2 is presented as a moving average over 14 d (Fig. 10a) consistent with the frequency of lake [TP] measurements. The value of fr1 was less than 0.1 d^{-1}, with the exception of two peaks (late June and late September) caused by runoff events. Most of the values were between 0.02 and 0.08 d^{-1}. The more realistic estimate of flushing rate conditions, fr2, indicates generally an order of magnitude higher rate, relative to plug flow conditions (Fig. 10a). Phytoplankton growth rates could exceed fr2 only under idealized laboratory conditions (maximum of ~ 2 d^{-1}, Chapra 1997), e.g., non-limiting temperature, light, and nutrient availability conditions. Only under such idealized conditions would localized phytoplankton blooms be expected on the shelf in response to local P inputs. However, actual net phytoplankton growth rates are generally substantially less than fr2 because of nutrient and light limitation to growth and the operation of an array of loss processes (Chapra 1997). Potential short-term increases in P availability from runoff events would tend to be compensated for by reduced light available from the attendant increase in light attenuation from the high levels of tripton. Accordingly, the flushing rate of the shelf is sufficient to prevent local blooms there and systematic gradients in phytoplankton biomass extending toward the pelagic zone.

The elongated shape of Cayuga Lake and its orientation along a prevailing wind direction promotes internal seiches (e.g., tilting of the metalimnion) and internal waves (horizontal water movements associated with shearing flow at metalimnetic interfaces) in response to wind events. In the extreme, this can cause upwelling events (Mortimer 1952, Wetzel 2001). These wind event-based mixing processes augment the effects of the circulation currents that routinely drive the flushing of the shelf described above. Upwelling events (i.e., wind out of the south) have been manifested in abrupt decreases in temperature measured by the near-surface thermistor on the shelf, as illustrated for 2004 (Fig. 10b) and 2005 (Fig. 10c). These events are irregularly timed, consistent with the stochastic character of wind events in the region. The events are clear signals of intrusion of metalimnetic (and even upper hypolimnion) waters onto the shelf and the associated abrupt flushing of this shallow area.

Results from the August 6, 1996 transect of the entire lake for the upper 30 m depict relatively uniform features of thermal stratification, with locally warmer near-surface waters in the shallow northern end of the lake (Fig. 11a). Substantial longitudinal and vertical structure was observed for *c*(660) (Fig. 11b). The pattern suggests sources of light scattering particles from the shelf area, with transport northward. The signal was diminished at site 8, and was essentially absent at locations beyond 20 km from the south end of the lake. The indicated signal apparently depicts the effects of tripton inputs to the shelf received from a runoff event on August 1, 1996 that resulted in a daily average flow in Fall Creek of 9.0 m^3/s). The estimated range of SD values extended from about 2 m (leaving the shelf) to approximately 3 m at mid-lake (based on Fig. 8a). Beyond the similarity of the general south to north gradient observed for

$[\mathrm{Chl}]_f$ for this transect (Fig. 11c), there were substantial differences from the $c(660)$ pattern that further support the disconnect between phytoplankton biomass and clarity in this lake. The higher levels of $[\mathrm{Chl}]_f$ extended substantially deeper (e.g., 0 to 15 m) than for $c(660)$ (e.g., 0 to 5 m). Moreover, the longitudinal gradient in $[\mathrm{Chl}]_f$, ~ 10% decrease over about 30 km, was smaller than that for $c(660)$ (~ 20% decrease). This modest gradient in $[\mathrm{Chl}]_f$ may reflect the effects of the localization of P loading at the southern end of Cayuga Lake. The extent to which this suggested stimulation of phytoplankton growth from these inputs is recurring, or is linked to runoff events, is unknown.

Modeling Needs

Phosphorus and Cultural Eutrophication

The above analyses provide insights related to the need for water quality models, appropriate target constituents, and attributes necessary to address the issues and adequately represent the lake. The water quality issues of silt/sediment and phosphorus are subject to some confusion for the southern shelf of Cayuga Lake because of the contribution terrigenous minerogenic tripton makes to the metrics of both turbidity [i.e., T_n, $c(660)$, and SD] and [TP] (in the form of PP). These signatures are particularly conspicuous on the shelf following runoff events (e.g., Fig. 5b and d) in response to elevated inputs of this material from the tributaries (Fig. 2a and c). The value of [TP] (as well as SD) has been demonstrated here to be a flawed metric of trophic state, particularly on the shelf. Exceedances of the 20 µg/L [TP] guidance value on the shelf would not occur without the contribution of tripton (Fig. 4a and b, Fig. 7a). It's reasonable to interpret the inclusion of the shelf phosphorus issue on the 303d list as a concern for cultural eutrophication effects, not terrigenous turbidity. The minerogenic tripton form of the elevated [TP] levels of the shelf does not itself establish this fraction as innocuous with respect to nutrient supply to algae, as desorption from such particles has been observed to be an important source in certain systems (James et al. 1997). The monitoring record for summer average [Chl] on the shelf depicts only a modest dependence on local P loading (Fig. 4d). However, significant differences in summer average [Chl] were not observed between the shelf and the pelagic zone over the 1998-2007 period (Fig. 4a), despite the localized P loading to the shelf (Fig. 2). High levels of flushing of the shelf through mixing with pelagic waters (Fig. 10) discourages the development of gradients in phytoplankton biomass from the local P loading, a transport feature that needs to be represented in any model that describes this portion of the lake.

Rather than a phosphorus model or perhaps more complex nutrient-phytoplankton model (Chapra 1997) that would focus on the shelf, a lake-wide framework is recommended to support future management deliberations for the entire lake. Certain features of the limnological observations and resource issues are supportive of the development of such a predictive tool, including: (1) the trend of increasing mobilization of P in the hypolimnion (Fig. 2a), (2) the modest dependence of the summer average shelf [Chl] on the local P loading (Fig. 4d), (3) the modest south to north gradient in $[Chl]_f$ documented in the transect of 1996 (Fig. 11c), (4) continuing development within the watershed, (5) the great resource value of the lake, and (6) uncertainties in the potential responses to future shifts in drivers (e.g., climate change). A credible nutrient water quality model would have great value in supporting related management evaluations for the lake and its watershed, by providing predictions for “what-if” scenarios. The constructs of the model framework would guide the identification and design of needed supporting studies for specification of inputs, and thereby the scope of monitoring and process studies. Accordingly, the water quality model could act as a valuable integrator of pertinent information and studies. Moreover, it can serve as a research tool to develop and test related hypothesis. The lake monitoring and tributary loading estimates reported here would contribute to the set-up and testing of such a model, though such efforts would need to be expanded to the rest of the lake and other important inputs.

A dynamic two-dimensional (vertical and longitudinal segmentation) hydrothermal/transport model (Martin and McCutcheon 1999) is recommended to serve as the physical framework for this water quality model. Such a framework could provide the necessary simulations of the features of the stratification/mixing regime, represent the impacts of localized nutrient loading on [Chl] patterns along the lake's axis, and support simulations over the seasons of interest for phytoplankton growth. Assignment of the shelf, as specified here, as the southern most model segment would be appropriate to continue to address water quality issues on the shelf. This same physical submodel could also accept other water quality submodels for the lake, as management interests and related information expands. However, given the noteworthy contribution tripton-based P makes to the P pool, particularly on the shelf, this fraction will need to be explicitly or implicitly represented in the model (subsequently).

Turbidity and Clarity

In sharp contrast to the phosphorus issue, clear signatures of silt/sediment impact have been resolved on the shelf in the form of elevated *c*(660) (and T_n) levels (e.g., Fig. 5d), in response to runoff event inputs (Fig. 3d, Fig. 6, Fig. 7c). The conspicuous coupling of tributary signals and the imparted signatures on the shelf represents a modeling opportunity. Adoption of a surrogate of light scattering, *c*(660) or T_n, as a model state variable, is recommended, instead of [TSS], given the close coupling of the public's perception of water quality to clarity (Smith and Davies-Colley 1992; Fig. 8a) and the extent of disconnect between metrics of light scattering and TSS for minerogenic particles (Fig. 9a and b) in this system. A water quality model is recommended that would simulate the terrigenous component of tripton (Table 1) received from tributary inputs, with the focus on the impacts of runoff events on the shelf. This component, when added to phytoplankton and $CaCO_3$ components, would represent the overall measured $c(660)$

$$c(660) = c(660)_t + c(660)_{Chl} + c(660)_w \tag{6}$$

where $c(660)_t$, $c(660)_{Chl}$, and $c(660)_w$ are the components associated with terrigenous tripton, phytoplankton biomass, and $CaCO_3$, respectively. The additive character of these various components of light scattering is appropriate because c is an inherent optical property (Davies-Colley et al. 1993, Kirk 1994). Values of $c(660)_{Chl}$ and $c(660)_w$ could be specified (not simulated) based on the long-term measurements. These values are small for the shelf when $c(660)$ is high from runoff events (Fig. 5d). A model of terrigenous $c(660)$ that adopted multiple fractions of $c(660)$ that settled at different rates was recently developed and tested for a reservoir (Gelda and Effler 2007). This approach may also be appropriate for Cayuga Lake. Monitoring to date (e.g., Upstate Freshwater Institute 2006) indicates the sediment resuspension source (Bloesch 1995) of $c(660)$ is small relative to external loads during the intervals of greatest silt/sediment impacts, and thus need not be resolved in an early version of the model.

Simulations of terrigenous $c(660)$ levels could also support predictions of this component of [TP] and [TSS] and differences in these metrics between the shelf and pelagic zone (e.g., Fig. 8g), based on empirical relationships developed from paired measurements with $c(660)$. Substantial variability in the $c(660)$ – [TSS] relationship is to be expected, in light of the system-specific information presented above on the different particles size dependencies of light scattering and gravimetric attributes (Table 1, Fig. 9). Management concerns for the spatial patterns of impact relative to potential recreational activity (e.g., bathing beach) on the shelf, together with the spatial heterogeneity documented following runoff events (Fig. 5d and Fig. 6), dictate the need for high spatial resolution, including in the lateral dimension, for the transport framework. These needs can be met with a three-dimensional hydrodynamic/transport model. Such frameworks can be appropriately used for short-term (e.g., days to weeks) simulations consistent with a focus on effects of runoff events in Cayuga Lake (Martin and McCutcheon 1999). The operative water quality standard for the terrigenous tripton model in a TMDL analysis may be the state's swimming safety clarity limit of SD ≥ 1.2 m. The model could provide simulations of the spatial extent and duration of violations on the shelf, according to individual runoff event characteristics, as well as improvements that could be expected from implementation of management actions such as erosion control in the watershed (e.g., shifts in relationships of Fig. 3d). Kinetic representations, including number of size classes, partitioning amongst the classes, and associated settling velocities (Gelda and Effler 2007) found to be successful in this model could support description of the behavior of tripton-based P in the lake-wide P or nutrient phytoplankton model.

Noteworthy Observations

A number of noteworthy observations have been made in this report that have implications for management of water quality in Cayuga Lake. Here we highlight findings that are particularly critical to the understanding and management of this valuable ecosystem.

1. Inputs from Fall Creek and Cayuga Inlet dominated overall inflow to the southern end of Cayuga Lake from 1998 to 2007. Wide interannual variations in the overall inflow to the shelf were driven primarily by natural variations in runoff from these tributaries. Average tributary flow ranged from about 2 m^3/s in 1999 to 14 m^3/s in 2004.

2. The concentration of SRP in the hypolimnion withdrawn by the LSC facility increased over the 2000 to 2006 interval from ~ 5 to ~ 9 µg/L on average. This has shifted the LSC load of this bioavailable form of phosphorus higher.

3. Treatment upgrades at the Ithaca Area WWTP resulted in a 1.5-fold decrease in total phosphorus loading from this facility for the 2002 – 2005 interval relative to 1998 – 2001, and a 3.7-fold decrease in 2006 and 2007 from the 1998-2001 interval.

4. Particulate froms of phosphorus represented approximately 67% of the total phosphorus loading to the shelf over the 1998 – 2007 period. WWTP inputs represented the majority of the loading of dissolved phosphorus in the earlier portion of the 1998 – 2007 period, particularly in the low runoff years of 1999 and 2001. However, increased contributions from the tributaries in high runoff years, such as 2004 and 2006, masked the benefits of the major reductions in loading from the point sources. The contribution of the LSC discharge has generally been relatively minor. However, under low flow conditions and following the upgrades in treatment at the WWTPs, such as prevailed in 2007, LSC represented about 7.5% of the P loading to the shelf.

5. Flow-weighted total phosphorus concentrations for the major inputs to the south shelf (Fall Creek, Cayuga Inlet, Ithaca Area WWTP, Cayuga Heights WWTP, LSC) ranged from ~ 45 µg/L in 2007 to ~ 120 µg/L in 1998. Largely progressive decreases in the dissolved component were calculated over the 2001 to 2007 interval. The particularly low value for 2007 reflects the combined effects of low tributary flow and increased treatment at the Ithaca Area WWTP.

6. Turbidity levels in Fall Creek and Cayuga Inlet increased at higher levels of runoff, in a manner similar to that observed for particulate phosphorus. Significant positive relationships prevailed between particulate phosphorus and turbidity, linking the phosphorus content and light scattering attributes of these terrigenous particles. The particles in Fall Creek were significantly more enriched with phosphorus than in Cayuga Inlet; the average particulate phosphorus ÷ turbidity ratios were 4.9 and 3.1, respectively.

7. Noteworthy differences in total phosphorus levels between the shelf and the pelagic site were a recurring feature during the 1998 – 2007 period. Summer average total phosphorus concentrations exceeded the New York State guidance value of 20 µg/L in pelagic waters in only two (1968 and 1994) of the eighteen years of the record. However, this threshold was exceeded in eight of the thirteen years of monitoring of the shelf, a condition that doubtless was a primary driver for the 303d listing and designation of phosphorus as a "cause/pollutant".

8. Multiple lines of evidence indicate that total phosphorus levels are higher on the shelf than in pelagic waters because of higher non-phytoplankton particle contributions of phosphorus, received primarily in the form of particulate phosphorus from stream inputs. Particulate phosphorus is the dominant form of phosphorus in the lake's upper waters representing > 65% on the shelf and in the pelagic zone, on average.

9. Runoff events caused local enrichment of forms of phosphorus, particularly particulate phosphorus, and turbidity on the shelf that diverged strongly from lower levels maintained in pelagic waters. Substantial spatial heterogeneity was commonly manifested for particulate-based metrics on the shelf during these intervals indicating the associated short-term loads were not evenly distributed throughout the shelf.

10. The generally higher total phosphorus and turbidity levels on the shelf compared to pelagic waters are shown to reflect inputs of clay particles from tributaries. The particle sizes of this material are shown to be in the 1 to 10 μm range.

11. Summer average chlorophyll concentrations increased from the late 1960s to the 1970s but have been lower since the mid-1990s. The lower levels of phytoplankton biomass over this interval may reflect the effect of various drivers, including New York's continuing ban on high P detergents (since the early 1970s), improved municipal wastewater treatment and invasion of the zebra mussel. No systematic decrease has yet occurred in chlorophyll concentrations in response to the recent reduction in P loading from the Ithaca Area WWTP.

12. Interannual variations in chlorophyll have not been significantly correlated with those for total phosphorus or clarity, on the shelf or in the pelagic zone. Moreover, chlorophyll levels at the pelagic site were independent of interannual differences in phosphorus loading to the shelf. However, 67% of the interannual variability in chlorophyll on the shelf was explained by differences in total dissolved phosphorus loading.

13. Summer average Secchi disc values in pelagic waters were systematically higher than those on the shelf throughout the 1998-2007 period, 1.3-fold on average. Multiple lines of evidence support the position that these spatial patterns, as well as temporal features, of light scattering and clarity in the lake are regulated more by tripton than phytoplankton biomass.

14. Phytoplankton biomass, as represented by chlorophyll concentration, was not a significant regulator of the dynamics of clarity on the shelf, and explained only a modest percentage (~ 25%) of the variations observed at the pelagic site.

15. Interannual variations in SD have been strongly correlated with those for total phosphorus for both the shelf ($r = 0.89$, $p = 0.00014$) and the pelagic site ($r = 0.7$, $p = 0.036$). This feature is consistent with a greater susceptibility of the near-shore area of the shelf to variations in tripton inputs, particularly from the tributaries.

16. Despite the phosphorus loading received from local sources, summer average total phosphorus and chlorophyll levels are not significantly higher on the shelf compared to bounding pelagic waters because of the high flushing rate of the shelf promoted by mixing with pelagic waters. During the May – October interval of 2001 the shelf flushed at an average rate of nearly once per day.

17. Intrusions of metalimnetic or upper hypolimnetic waters onto the shelf, known as upwelling events, were observed to occur frequently during the summer stratification period. These events are caused by wind events that produce internal seiches and promote rapid flushing of the shallow southern shelf area.

18. A single longitudinal transect of the lake conducted on August 6, 1996 suggests sources of light scattering particles from the southern shelf area and transport northward. A comparatively modest south to north gradient in chlorophyll concentrations may reflect the effects of local phosphorus loading at the southern end of Cayuga Lake.

19. Two water quality modeling initiatives are recommended to guide related management deliberations: (1) a lake-wide seasonal phosphorus or nutrient-phytoplankton model, with a two-dimensional transport framework that would provide longitudinal and vertical resolution, and (2) a shorter-term three-dimensional model for the inorganic particle component of light scattering that would simulate the dynamics and spatial details of the impacts of runoff events on clarity levels on the shelf.

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Table 1. Summary of SAX results for Cayuga Lake.

Site	Date	T_n (NTU)	b_m (m^{-1})	b_m type distribution (%) Clay	Ca-rich	Quartz	Ca-agg	Misc	d_{50}/b_m (μm)	d_{50}/VV_m (μm)
Fall Creek	30 Jun 04	6.1	2.67	80.6	0.7	8.6	3.3	6.92	3.9	8.7
5		1.4	0.48	74.9	1.2	15.5	3.6	4.82	3.1	5.4
8		0.6	0.21	76.8	3.8	8.7	4.0	6.77	4.9	7.6
Fall Creek	29 Jul 04	99.5	37.76	85.0	1.1	8.9	1.2	3.88	4.2	8.0
5		2.1	1.09	28.6	37.	2.9	27.9	2.92	2.3	4.2
8		2.1	0.66	16.3	51.4	1.9	26.6	3.80	2.3	4.0

Figures

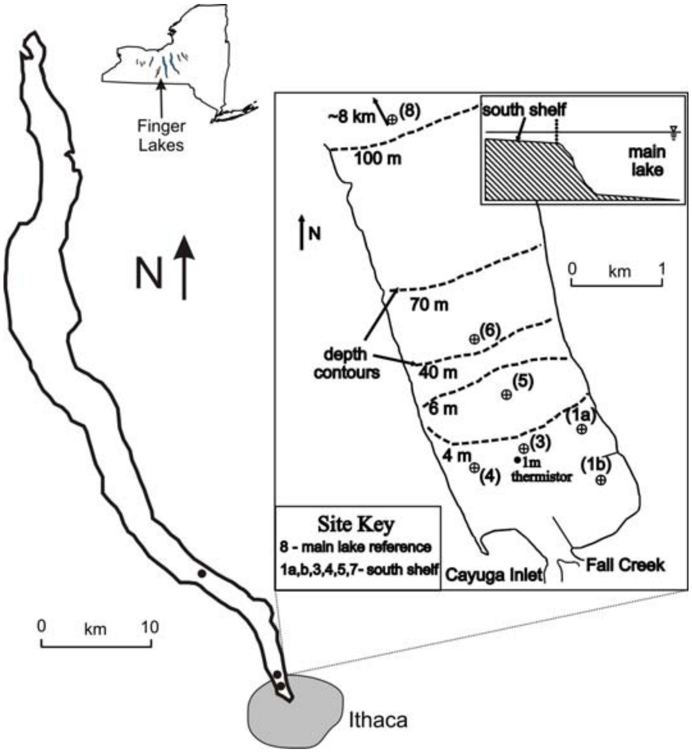

Figure 1. Setting, sampling sites for Cayuga Lake, bathymetry for southern shelf, position within Finger Lakes and New York.

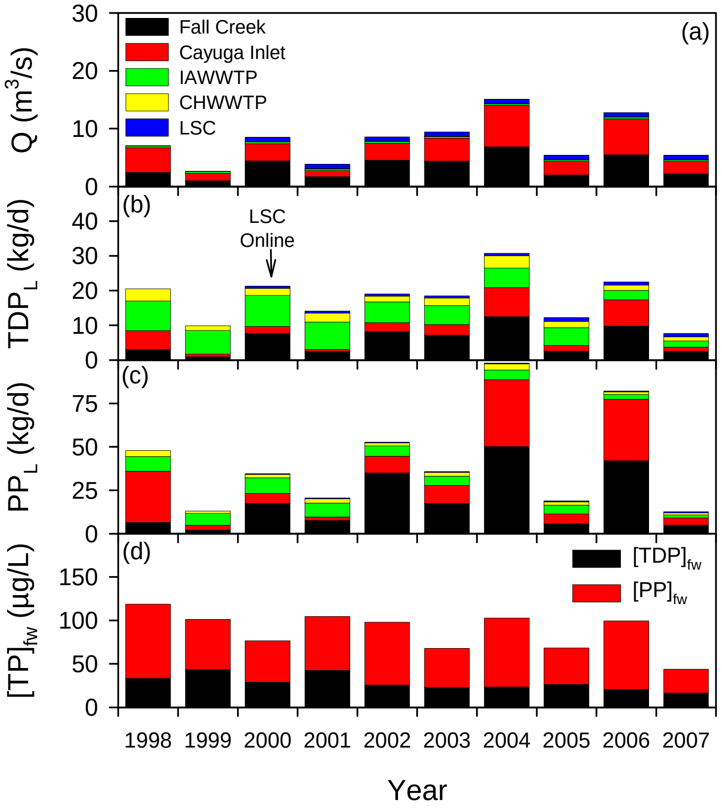

Figure 2. Annual average tributary and discharge conditions for the April-October interval over the 1998-2007 period, partitioned according to input: (a) flow rate, Q, (b) total dissolved phosphorus loading rate, TDP_L, (c) particulate phosphorus loading rate, PP_L, and (d) volume-weighted total phosphorus concentration, $[TP]_{fw}$. Loads (a-c) partitioned according to five inputs; $[TP]_{fw}$ partitioned accord in $[TDP]_{fw}$ and $[PP]_{fw}$ components.

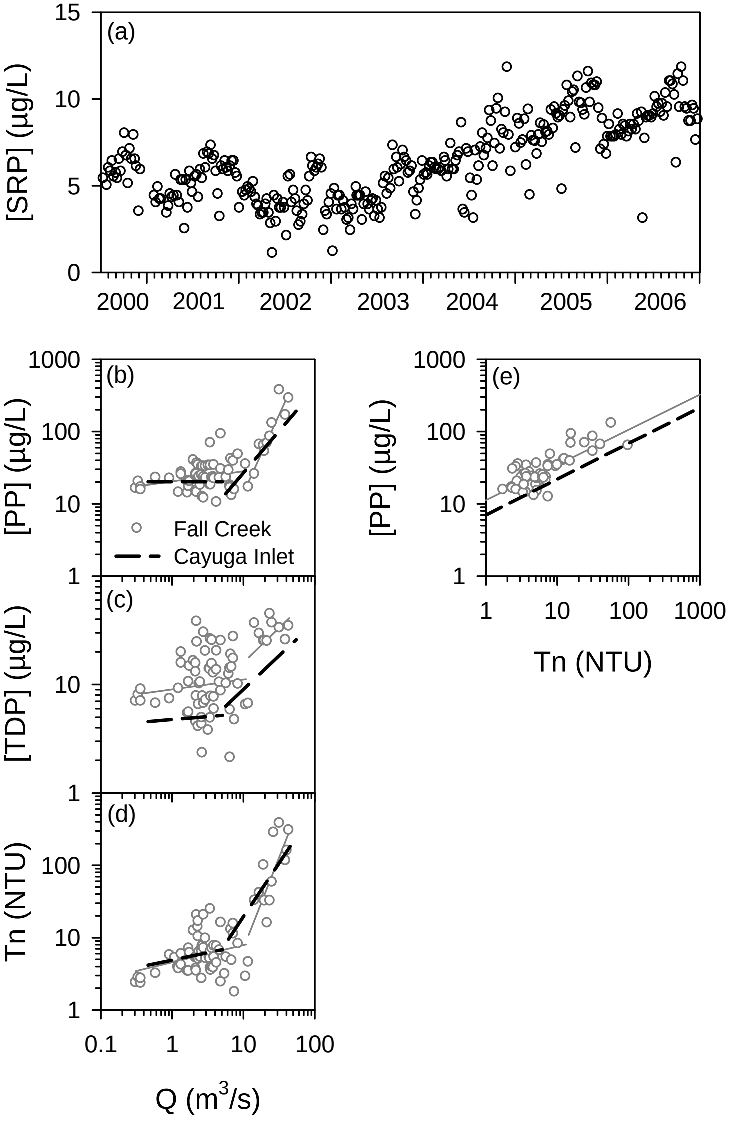

Figure 3. Constituent levels and relationships for inputs to the shelf of Cayuga Lake: (a) [SRP] in LSC intake (equal to discharge) over the 2000 – 2006 interval, (b) [PP] versus Q relationships for Fall Creek and Cayuga Inlet, (c) [TDP] versus Q relationships or Fall Creek and Cayuga Inlet, (d) T_n versus Q relationships for Fall Creek and Cayuga Inlet, and (e) [PP] versus T_n relationships for Fall Creek and Cayuga Inlet. Supporting observations from Fall Creek included, but not for Cayuga Inlet, (f) – (d).

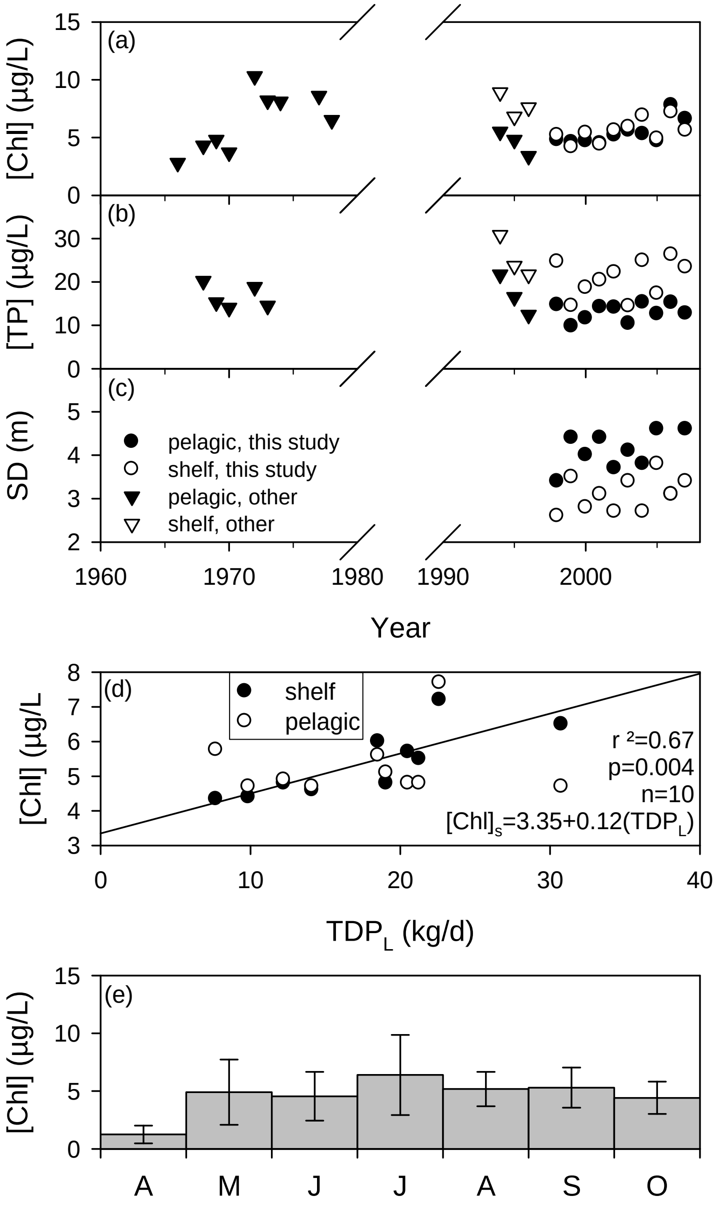

Figure 4. Long-term trends in common trophic state metrics for Cayuga Lake: (a) summer (June-September) average [Chl], (b) summer average [TP], (c) summer average SD, (d) evaluation of relationships between summer average [Chl] and TDPL to the shelf over the 1998-2007 period, and (e) seasonal pattern of [Chl] for the 1998-2007 period as monthly means with ± 1 standard deviation as vertical bars.

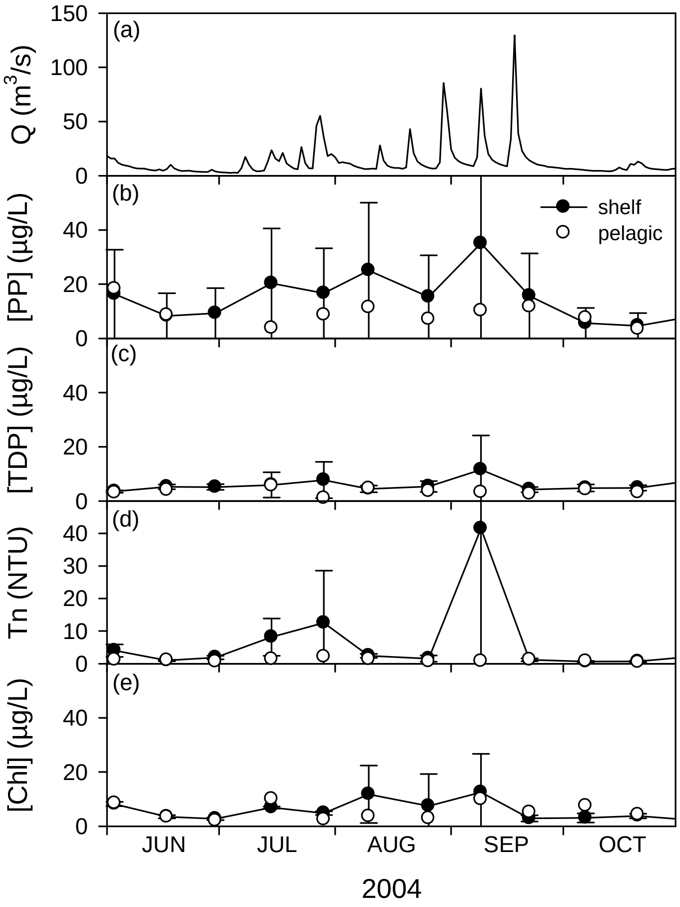

Figure 5. Comparative dynamics for the shelf and a pelagic site on Cayuga Lake for the June – October interval of 2004: (a) daily tributary flow (summation of Fall Creek and Cayuga Inlet), (b) [PP], (c) [TDP], (d) T_n, and (e) [Chl]. Shelf values are averages; limits of vertical bars for shelf observations correspond to ± 1 standard deviation based on all shelf observations.

Figure 6. Aerial photograph of the southern end of Cayuga Lake that depicts turbid plumes and non-uniform distribution on the shelf.

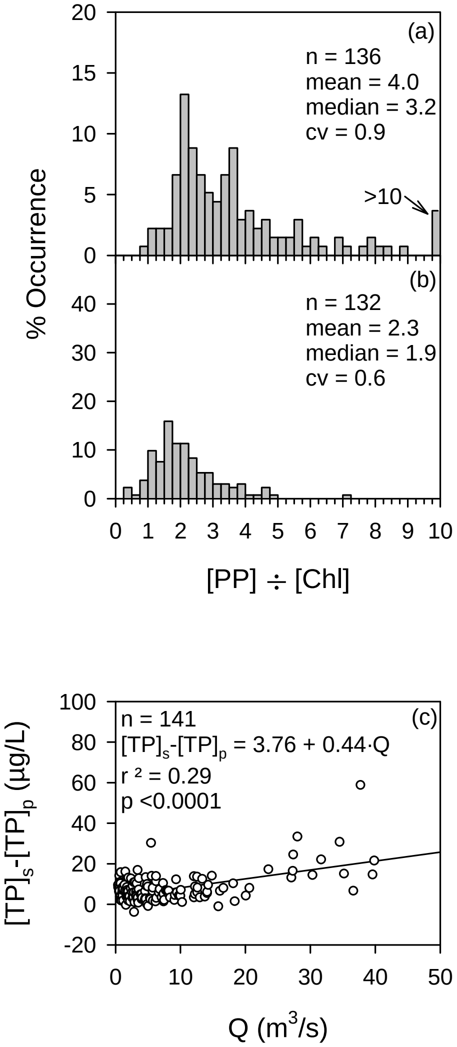

Figure 7. Phosphorus relationships on the shelf and at a pelagic site on Cayuga Lake for the 1998 – 2007 period: (a) distribution of occurrence of the [PP] ÷ [Chl] ratio on the shelf, (b) distribution of occurrence of the [PP] ÷ [Chl] ratio at the pelagic site, and (c) dependence of the residual of shelf [TP] ($[TP]_s$) and pelagic TP ($[TP]_p$) values on the tributary (Fall Creek plus Cayuga Inlet) flow (Q) to the shelf.

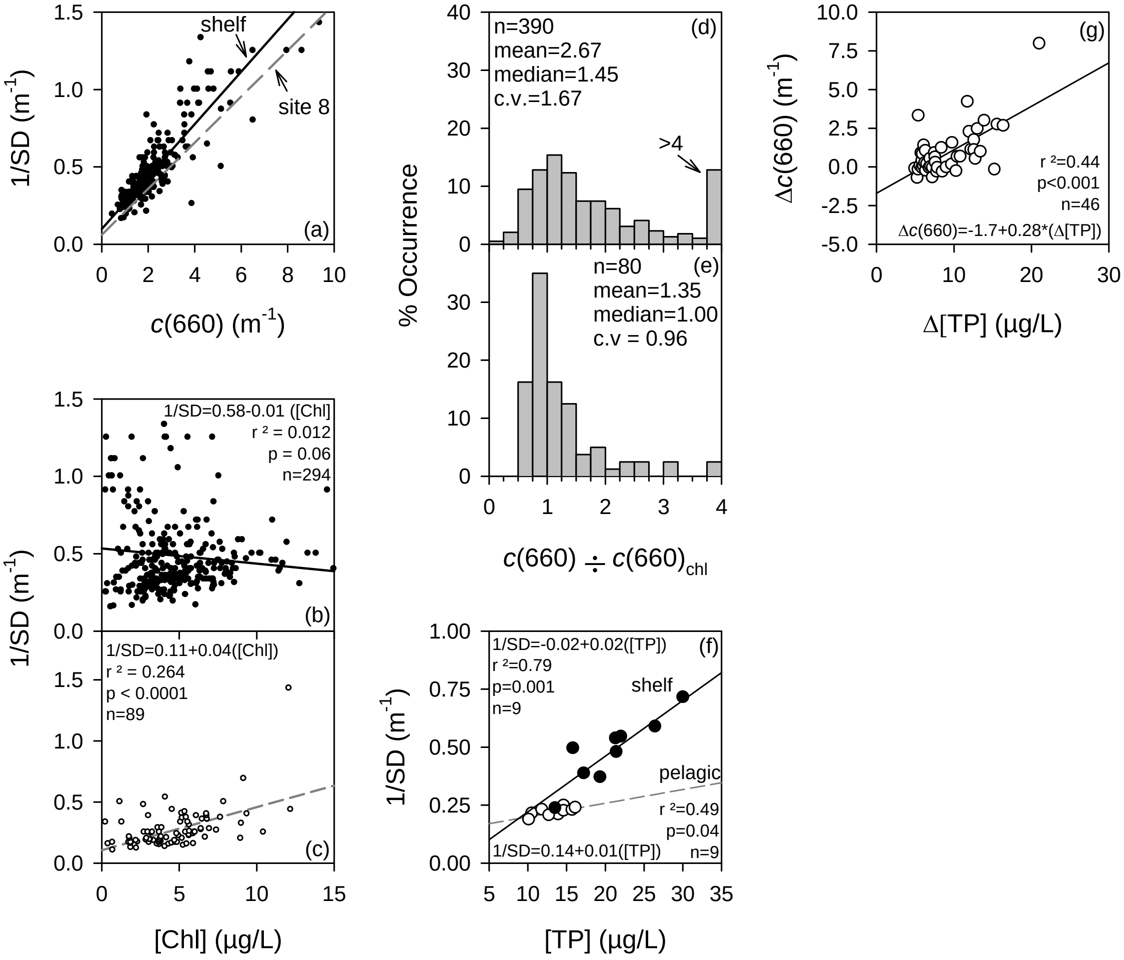

Figure 8. SD and *c*(660) relationships for Cayuga Lake for the 1998 – 2007 period: (a) dependence of 1/SD on *c*(660), (b) dependence of 1/SD on [Chl] for the shelf, (c) dependence of 1/SD on [Chl] for the pelagic site, (d) distribution of the *c*(660) ÷ *c*(660)Chl ratio for the shelf, (e) distribution of the *c*(660) ÷ *c*(660)Chl ratio for the pelagic site, (f) dependence of 1/SD on [TP] for summer average conditions on the shelf and at the pelagic site, and (g) relationship between the spatial residuals (shelf average minus pelagic) of *c*(660) (Δ*c*(660)) and [TP] (Δ[TP]).

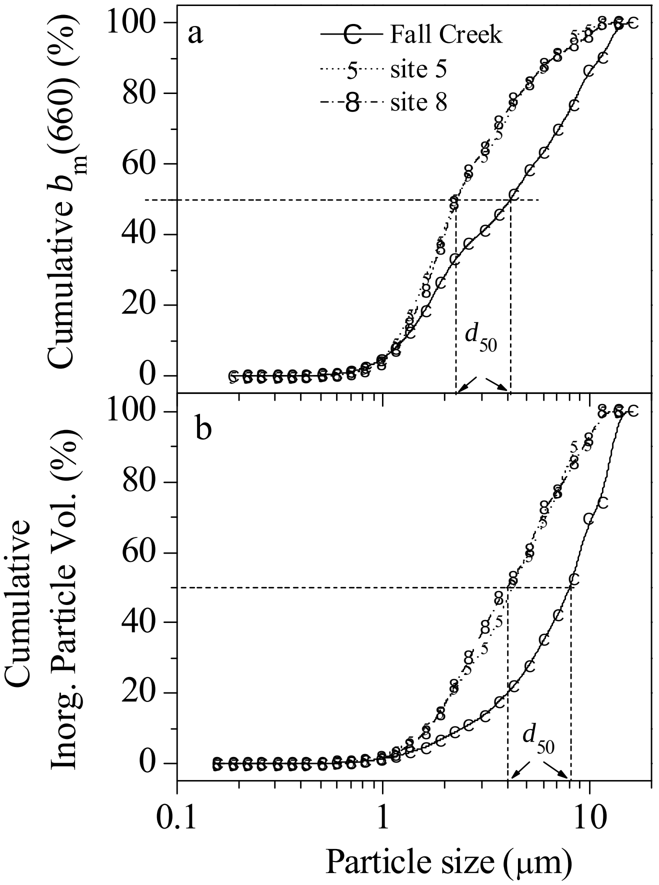

Figure 9. Size dependencies of attributes of minerogenic particles in Fall Creek, on the shelf (site 5), and in pelagic waters (site 8) of Cayuga Lake, July 29, 2004 from SAX: (a) b_m, the minerogenic light scattering coefficient, from Mie theory calculations, and (b) VV_m, the minerogenic particle volume per unit water.

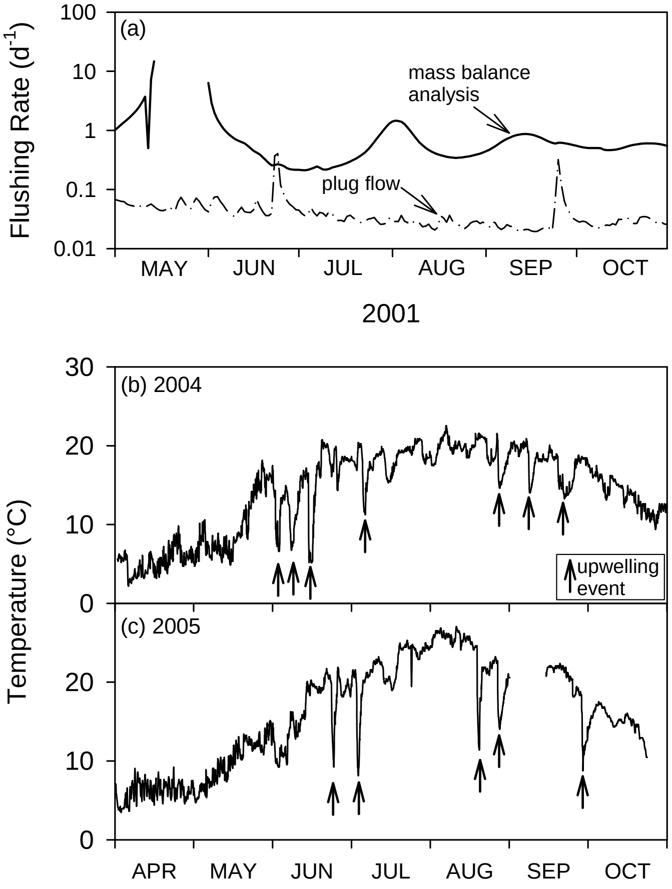

Figure 10. Hydrodynamic and transport features for the shelf of Cayuga Lake: (a) dynamics of flushing rate on the shelf, based on mass balance analysis and for the plug flow assumption, (b) time series of hourly surface temperatures at the southern end of the lake for the April – October interval of 2004, and (c) time series of hourly surface temperatures of the southern end of the lake for the April – October interval of 2005. Occurrences of conspicuous upwelling events identified by arrows in (b) and (c).

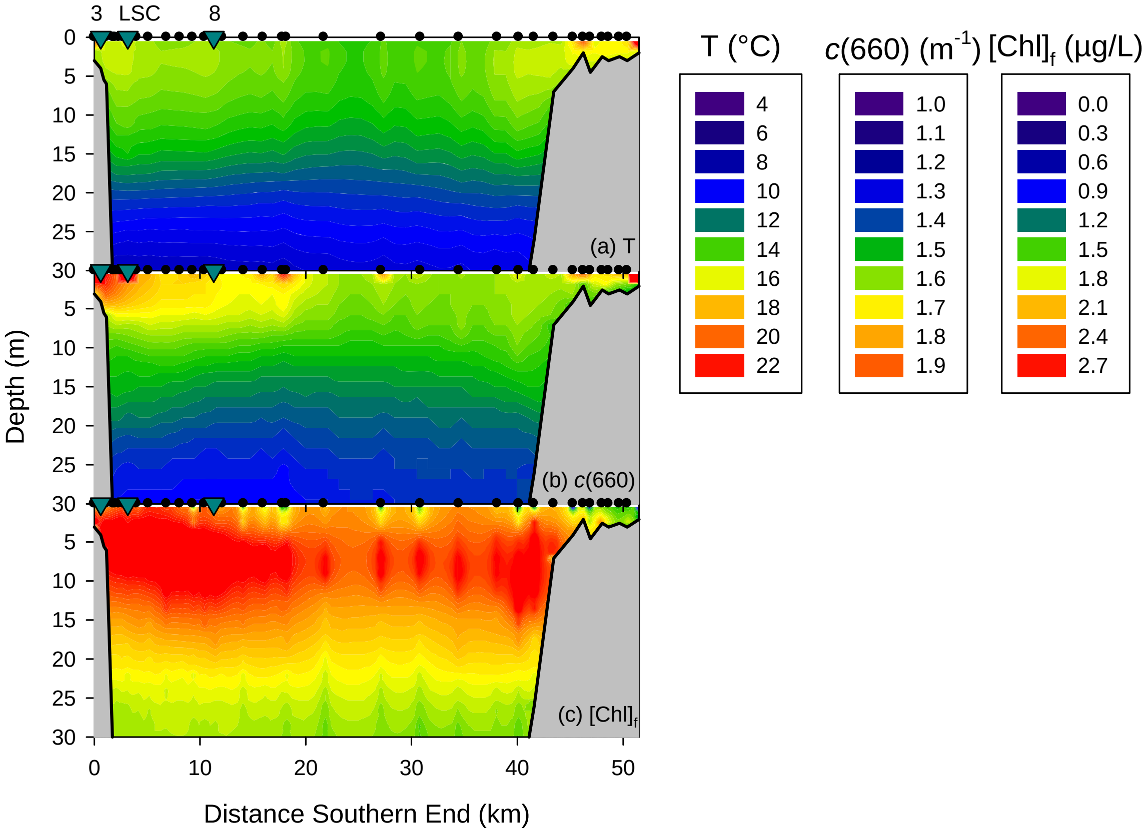

Figure 11. Longitudinal and vertical (0 to 30 m) patterns along the primary axis of Cayuga Lake on August 6, 1996 as color contours: (a) temperature, (b) *c*(660), and (c) [Chl]$_f$.