Evaluation of the Cost and Benefit of Applying Aluminum (alum) to Little St. Germain Lake Sediments

Prepared for
Little St. Germain Lake Protection and Rehabilitation District

December 2007

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Executive Summary

Sediment was collected at 26 locations in Little St. Germain Lake on June 14th, 2007, to determine the expected cost and benefit of treating the lake sediments with aluminum (alum). Sediment core sections 28 to 38 cm long were taken in deep and shallow areas of the lake and in each bay to determine the spatial distribution of phosphorus (mobile, aluminum-bound, and organic bound), potential phosphorus release rates, and appropriate alum doses. The distribution of phosphorus (mobile fraction) is shown in Figure Ex-1. Overall, the concentration of phosphorus in the lake sediments was high, even when compared to lakes in urban areas, and there is a high potential for internal phosphorus loading to affect water clarity in the lake. The sediment data indicate that the highest phosphorus was in the West Bay, followed by the South Bay, Upper East Bay, East Bay, and then No Fish Bay.

Although there is a potential for internal phosphorus loading to affect phosphorus levels in the water column of each bay, factors such and dissolved oxygen levels, bathymetry, the volume of each bay, stratification, and the transport of phosphorus from the lake bottom, determine whether high phosphorus in sediment actually results in high phosphorus in the surface waters (and hence high algal growth). Water quality models were developed to evaluate the expected change in phosphorus in the East/Upper East and South Bay with alum treatment. A model was not developed for the West Bay because water monitoring data collected in 2007 indicate that the potential for phosphorus transport to the surface of this bay to be minimal, and phosphorus levels are very low in the summer. The results of the modeling work, provided in Table Ex-1, indicate that there will be a significant water clarity benefit to the Upper East and East Bay as well as the South Bay (water from the East Bay has a significant effect on South Bay phosphorus levels) if the Upper East and East Bay are treated with alum at the doses prescribed (indicated below). The additional benefit of treating the South Bay in addition to the Upper East and East Bay should be weighed against the additional cost of treating the South Bay. The primary benefit of treating the South Bay will be a reduction in spring to early summer algal blooms and reduced potential for and magnitude of late summer blooms. It may be advisable to first treat the Upper East and East Bay to discern whether the water quality improvement in the South Bay is adequate with only the treatment of the Upper East and East Bay.

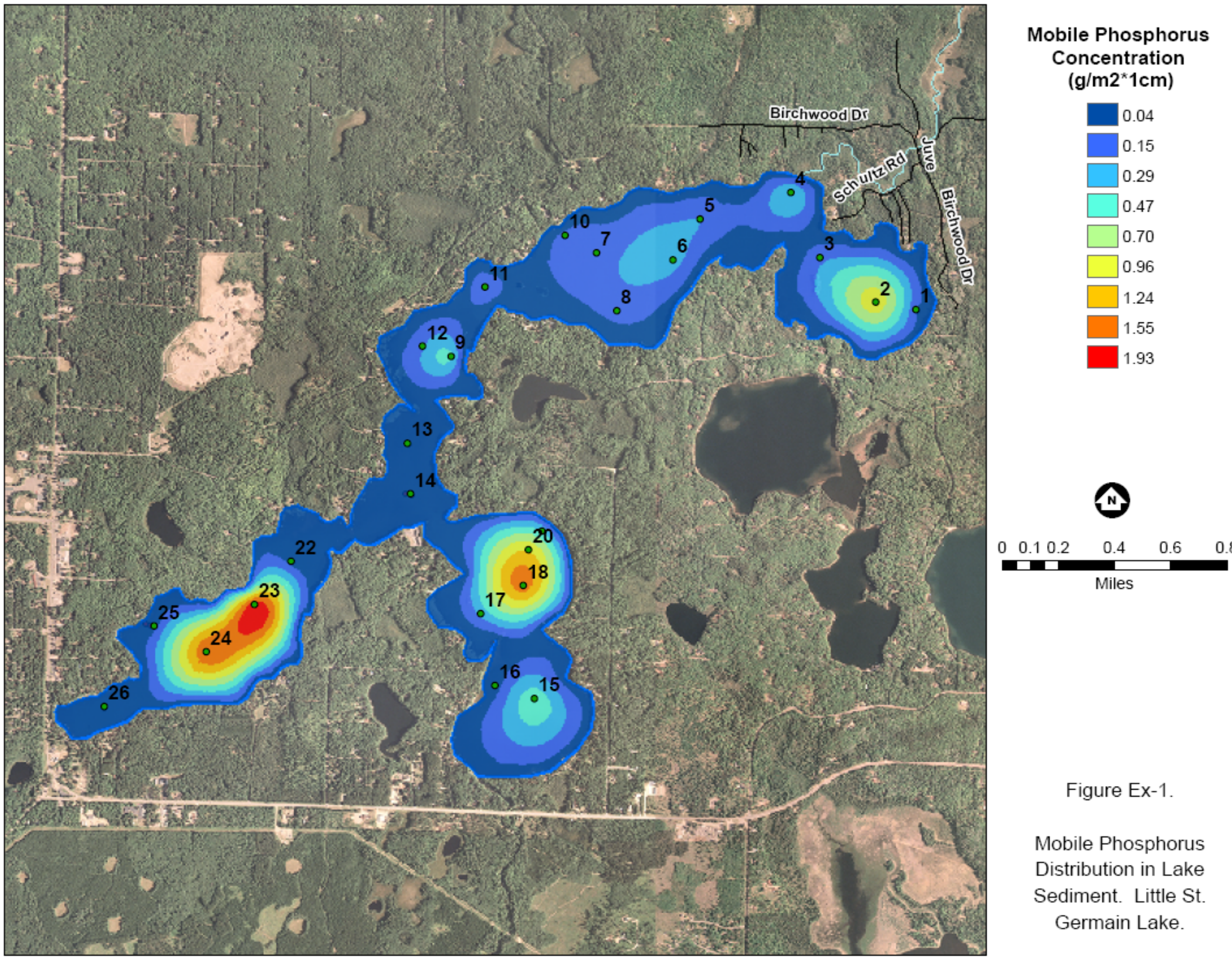

Figure Ex-1.

Mobile Phosphorus Distribution in Lake Sediment. Little St. Germain Lake.

Table Ex-1. Expected Improvement in Total Phosphorus, Chlorophyll *a*, and Secchi Disc Depth (June through August) with Alum Treatment of the East/Upper East Bay and the South Bay.

	East Bay/Upper East Bay			South Bay(2)		
Alum Treated Area	**Total Phosphorus (mg/L)**	**Chlorophyll a (µg/L)**	**Secchi disc depth (ft)**	**Total Phosphorus (µg/L)**	**Chlorophyll a (µg/L)**	**Secchi disc depth (ft)**
No Treatment	0.062	38	2.8	0.046	19	4.4
East/Upper East Bay Only(1)	0.033	15	4.2	0.028	10	6.0
South Bay Only	0.062	38	2.8	0.035	13	5.3
South Bay and East/Upper East	0.033	15	4.2	0.019	6	7.6

(1)Average of modeling results for 2001, 2002, and 2007. Average for June through August period.

(2)Average of modeling results for the year 2002.

The recommended alum application doses and estimated costs are provided in Table Ex-2. The recommended treatment areas are provided in Figure Ex-2. The treatment area includes the Upper East and East Bay, and the South Bay. Treatment is recommended for the entire bay to a minimum depth of 6 feet. Because the alkalinity of the lake is approximately 50 mg/L as $CaCO_3$, it will be necessary to split the alum dose for the Upper East and East Bay in half, and apply half of the dose during one year and the other half in the subsequent year. It may be necessary to split the South Bay dose three times in order maintain acceptable pH levels during alum treatment.

Table Ex-2. Alum Application Doses, Potential Application Areas, and Costs.

Bay	Treatment Area (ac)	Total Gallons Applied	Gallons of Alum Applied per Acre	Estimated Cost
Upper East and East	325	365,565	1,125	$365,565
South	162	443,202	2,736	$443,202
West(1)	122	647,575	5,296	$647,575
Total	609	1,456,342	---	$1,456,342

(1) Not recommended for treatment.

Figure EX-2

Alum Application Areas
Little St. Germain Lake

1.0 Introduction

Sediment was collected at 26 locations in Little St. Germain Lake on June 14th, 2007, to determine the expected cost and benefit of treating the lake sediments with aluminum (alum). Sediment core sections 28 to 38 cm long were taken in deep and shallow areas of the lake and in each bay to determine the spatial distribution of phosphorus (mobile, aluminum-bound, and organic bound), potential phosphorus release rates, and appropriate alum doses.

Internal phosphorus loading was identified previously (Barr Engineering, 2007) as a potential cause of observed phosphorus levels in the Upper East and East Bay. The pattern of significant phosphorus increase in the mid to late summer in the Upper and East Bay strongly signifies the effect of internal phosphorus loading on phosphorus in the water column of the Upper East and East Bay. The effect of internal loading in the South Bay on phosphorus in the surface waters of this bay could not be deciphered from simple review of the monitoring data alone.

The goals of this study were as follows:

(1) Estimate the expected improvement in in-lake phosphorus, Secchi disc depth, and algae (chlorophyll *a*) with alum treatment of lake sediments.

(2) Use simple and complex lake models to quantify the benefits of alum treatment

(3) Determine the alum dose and application areas such that internal loading in the target areas is significantly reduced.

(4) Estimate the cost of alum treatment.

This report describes the results of sediment sampling and analysis that was conducted in June 2007, recommended alum doses, application areas, and costs, and in-lake modeling results with and without alum application.

2.0 Sediment Sampling and Analysis

2.1 Sediment Collection

In order to accurately determine internal phosphorus loading in a lake, it is important to properly characterize mobile phosphorus in the sediment of a lake both across the lake and within the sediment. A Wilner gravity coring device was used to collect sediment cores from 26 locations in Little St. Germain Lake on June 14th, 2007 (Figure Ex-1). Sediment from the top 28 to 38 cm of lake sediment was collected to determine the depth distribution of phosphorus in the sediment across the lake.

2.2 Sediment Analysis

Sediment samples were analyzed for water content by oven drying for 24 hours at 105 °C. Loss on ignition (LOI) of the samples was measured after combustion at 550 °C for 2 hours (Håkansson and Jansson 1983). The LOI result is used to determine percent organic matter and estimate sediment density.

A phosphorus fractionation method by Psenner et al. (1988) was used to separate the different forms of inorganic and organic phosphorus in the sediment. The fractions and their representative forms are as follows:

Table 1. Sediment phosphorus fractions and their associated forms.

Loosely sorbed P	Ion exchangeable and pore water phosphorus
Iron (and manganese) bound P (Fe-P)	Reductant soluble phosphorus
Aluminum bound P (Al-P)	Ligand exchangeable phosphorus
Organic bound P (Org-P)	Extractable biogenic phosphorus

The first two fractions, loosely sorbed and Fe-P constitute the mobile phosphorus pool that directly contributes to internal phosphorus loading from the sediment to the water column. Org-P represents a portion of sediment phosphorus that will degrade over time and contribute to the mobile phosphorus pool. The Al-P fraction was analyzed because it is needed to determine the amount of Org-P based on the fractionation procedure.

Mobile phosphorus was modeled using the Geostatistical Analysis extension in ArcGIS software to evaluate spatial trends in the data.

2.3 Sediment Results

Mobile phosphorus content in the sediment of Little St. Germain Lake varied greatly, both spatially and by sediment depth, and was highest in the deep bays located in the West and South bays.

- North, Upper East Bay (1-3), East Bay, (Cores 4-12)
- Mid, No Fish Bay (Cores 13-14)
- South, South Bay (17-20), Second South Bay (15-16)
- West, West Bay (22-26)

In nearly all cores collected, mobile phosphorus was highest near the sediment surface and decreased as sediment depth increases (Figure 1-3). Organic phosphorus also follows this same pattern but with concentrations typically higher than mobile phosphorus in most cores (Figures 4-6). This is typical in productive lakes (especially in shallow areas) where mobile phosphorus can be quickly recycled by algae as they grow.

The results shown on Figures 1 through 6 represent concentrations normalized by dry weight. This is useful for determining areas of excess concentration, but in order to determine the amount (or mass) of internal phosphorus loading, the total mass of mobile phosphorus must be determined. As seen in Table 2, mobile phosphorus mass varied greatly across the lake and ranged from 0.020 to 2.00 $g/m^2/cm$. The core numbers in this table correspond to the sampling locations shown on Figure Ex-1. The results for mobile phosphorus mass presented for each core are averages of the upper layers of sediment considered to have excess phosphorus. Alum doses for each bay (Table Ex-2) were calculated using the mobile phosphorus data in Table 2. Doses were calculated according the procedure by Pilgrim et al., 2007 (provided in Appendix A).

Table 2. Mass of surficial mobile phosphorus in sediment cores collected from Little St. Germain Lake.

Core #	Lake Depth (ft) Where Sampled	Sediment Section (cm)	Mobile Phosphorus (g/m2/cm)	Organic Phosphorus (g/m2/cm)
SG1	8.5	0-6	0.10	0.31
SG2	16	0-6	0.97	0.29
SG3	7	0-6	0.16	0.32
SG4	6	0-6	0.35	0.28
SG5	14	0-6	0.21	0.30
SG6	15	0-6	0.27	0.26
SG7	13	0-6	0.16	0.29
SG8	12	0-6	0.13	0.23
SG9	13	0-6	0.39	0.25
SG10	9	0-6	0.12	0.25
SG11	9	0-6	0.19	0.27
SG12	7	0-6	0.19	0.39
SG13	5	0-6	0.06	0.27
SG14	6	0-6	0.02	0.18
SG15	8	0-6	0.48	0.24
SG16	6	0-6	0.04	0.16
SG17	10	0-6	0.24	0.25
SG18	24	0-10	1.53	0.21
SG19	15	0-10	0.37	0.24
SG20	20	0-10	1.06	0.23
SG22	33	0-10	0.05	0.21
SG23	54	0-10	2.00	0.16
SG24	50	0-10	1.65	0.17
SG25	28	0-6	0.05	0.31
SG26	26	0-10	0.07	0.31

3.0 Water Quality Modeling

To quantify the expected water quality benefit with the treatment of lake sediment with alum, water quality models were constructed for the East Bay and the South Bay. Because the water quality of the East Bay and Upper East Bay are nearly identical (Figure 7) and are likely in equilibrium, it is reasonable to assume that the response of the Upper East Bay to alum treatment will be the same as the East Bay. The West Bay was not modeled because monitoring data collected in 2007 suggest that phosphorus in the bottom of the lake was not reaching the surface waters of the West Bay.

3.1 Water Quality Modeling Methodology

There were several steps in the modeling process for the East Bay: (1) development and calibration of a watershed yield model (P8) for Muskellunge Creek (see Figure 8) , (2) development and calibration of a finite-difference mass balance model for the East Bay using 2001, 2002, and 2007 data, (3) estimation of internal phosphorus loading using the sediment data (see Pilgrim et. al., 2007) and the calibrated model, and (4) prediction of the reduction of internal loading with alum treatment at the prescribed doses (see Table Ex-2), and (5) use of the calibrated model to determine phosphorus levels after alum treatment. The finite difference model is provided in Pilgrim and Brezonik, 2005, and is similar to a model provided in Thomann and Mueller, 1987. As a simplification it was assumed that the East Bay was completely mixed, however, it is recognized that monitoring data indicates the East Bay stratifies and mixes several times from the spring through the fall.

A similar procedure was followed when the South Bay was modeled, however, a more complex, one-dimensional model called DYRESM/CAEDYM (University of Western Australia, Center for Water Research) was used to evaluate the potential benefits of alum treatment on water quality in that bay. This model is capable of determining whether phosphorus released from bottom waters actually reaches the surface, and hence has the potential to cause algal blooms. This model was calibrated using in-lake water quality and physical measurement in 2001 and 2002. The potential benefit of alum treatment was evaluated for 2002. For 2002, inflows to the South Bay were assumed to equal the inflows from Muskellunge Creek (modeled flows), and the phosphorus levels in the inflows were assumed to equal to the modeled levels in the East Bay. It was assumed that inflow were equal to outflows. Other model inputs were climatological and direct lake precipitation (measurements taken at Rhinelander, WI).

3.2 Modeling Results

3.2.1 Calibration

Three different models were calibrated, meaning, models were developed and parameters adjusted such that the outcome of the model matched the monitoring data. The models were: (1) watershed yield model (P8), (2) finite difference lake model for the East Bay/Upper East Bay, and (3) and a one-dimensional lake model for the South Bay (does not include the South-South Bay).

The watershed model developed for Muskellunge Creek was completed using a program (P8) that is often used to predict runoff volume and water quality. Only the runoff volume component of the model was used. The primary inputs to this model were precipitation and temperature (from Rhinelander), and tributary watershed area. This model is typically used for urban systems; however, it has a sub-surface flow function that allows it to be used for undeveloped watersheds where most of the flow reaches a stream via the vadose zone. The model calibration (Figure 8) was adequate for lake modeling purposes. The model was used to predict flow in Muskellunge Creek in 2002 and 2007.

The primary inputs into the lake model for the East/Upper East Bay include lake volume, inflow volume (Muskellunge Creek, direct precipitation, and groundwater) and total phosphorus (based upon monitoring data in 2001, 2002, and 2007), outflow volume (assumed equal to inflows) and total phosphorus (assumed equal to in-lake total phosphorus), and internal loading rate. Based upon the in-lake monitoring data, internal loading was initiated on June 11 of each year (2001, 2002, and 2007). The only calibration factors were the net apparent settling rate for phosphorus (set at 6 meters per year) and the rate of phosphorus release from sediment (ranging from 1.3 to 3.0 mg m^{-2} d^{-1}). It should be noted that the phosphorus release rate is the actual release rate and not the maximum potential release rate. The actual release rate is affected by things such as wave action, stratification, dissolved oxygen levels, and temperature, while the potential release rate should be constant. The highest release rate was found in 2007 while dissolved oxygen levels were low and lake temperatures were high. Calibration results are provided on Figure 9.

A one-dimensional lake model DYRESM/CAEDYM (University of Australia, Center for Water Research) was used to simulate phosphorus dynamics in the South Bay of Little St. Germain Lake (not the South-South Bay). This model was used to determine the relative influence of water and phosphorus entering the bay from the East Bay and phosphorus release and transport from the lake sediments. There are a significant number of inputs to the DYRESM/CAEDYM model and primarily consist of climatological data (from Rhinelander, WI), inflow volume, chemistry and physical conditions, and bathymetry. Calibration of the model was conducted in a stepwise process for temperature, dissolved oxygen, phosphorus release, and finally for surface water phosphorus levels. The potential phosphorus release rate of 3.7 mg m^{-2} d^{-1} was based upon the collected sediment data and a relationship between potential release rate and mobile phosphorus concentration. The model was calibrated for 2001 and 2002 (see Figures 10 through 16), but because of limited time, model simulations with various alum treatment scenarios were conducted only for 2002.

3.2.2 In-Lake Water Quality With Alum Treatment

The effect of treating the sediments of the East and Upper East Bay with alum was provided in the executive summary (Table Ex-1). The modeling results with alum treatment are also provided on Figure 9d. The results show that without alum treatment, total phosphorus levels (in 2001, 2002, and 2007) in the summer can range from a low of around 0.03 mg/L (30 μg/L) in the spring to a high of 0.116 mg/L (116 μg/L) in the summer. The results show that with alum treatment, total phosphorus levels (in 2001, 2002, and 2007) in the summer can range from low of around 0.025 mg/L (25 μg/L) in the spring to a high of 0.042 mg/L (42 μg/L) in the summer. Based upon historical relationships (Figure 17) between total phosphorus and algae (chlorophyll a) levels, and a relationship between total phosphorus and water clarity (Secchi disc depth), average summer chlorophyll a levels will drop from 38 to 15 μg/L and Secchi disc depth will improve from 2.8 to 4.2 feet after alum treatment. However, it is expected that the improvement in clarity will be greater than that predicted by the model because the phosphorus fraction that is released from the lake sediment (PO_4) is more readily used for growth than the phosphorus fraction that is coming from Muskellunge Creek.

The effects of treating the sediments of the East and Upper East Bay and/or the South Bay with alum on the levels of phosphorus in the South Bay were provided in the executive summary (Table Ex-1). The modeling results as well as the monitoring data indicate that several factors affect phosphorus levels in the South Bay, they are: (1) internal phosphorus loading in the winter has the effect of producing very high phosphorus levels in the spring, (2) phosphorus levels in the East Bay have a significant effect on phosphorus levels in the South Bay during the summer, and inflows from the East Bay are the primary determinant of phosphorus levels in the South Bay during much of the summer, (3) the South Bay does not stratify until mid-late June, and destratifies in mid-August. This does not provide much time for anoxia to develop and phosphorus release to occur. Phosphorus release that does occur can increase August phosphorus concentrations by about 5 to 10 μg/L (0.005 to 0.010 mg/L). The change in phosphorus in the top 2 meters of the South Bay under several alum treatment scenarios is summarized on Figure 10b. It can be seen that with the treatment of the East and Upper East Bays there will be a significant improvement in the phosphorus levels of the South Bay even if there is no treatment in the South Bay. The primary benefit of treating the South Bay with alum will be a reduction in the potential for spring to early June algal blooms and the elimination of late summer algal blooms.

4.0 Conclusions and Discussion

This study made use of inflow, in-lake water quality, and flow data, as well as sediment phosphorus data to determine the effect of inflows and internal loading on phosphorus levels in the surface waters of Little St. Germain Lake. Little St. Germain Lake is a complex system because of the geomorphology, substantial inflows to the lake, and the very high phosphorus levels in the sediment. For water quality analysis, the East Bay and the South Bay were analyzed as separate systems. The West Bay was not modeled due to the limited effect internal loading has on this portion of the lake during the summer months.

It is clear that phosphorus release from the lake sediments of the East and Upper East Bay is the cause of the observed high phosphorus levels in the mid-to-late summer months. Alum treatment at the doses prescribed in this study will lead to significant reductions in phosphorus in the water column and reduce the magnitude and frequency of algal blooms. Because of the large inflows from Muskellunge Creek, Little St. Germain Lake will remain a productive, mesotrophic lake. Alum treatment of the East and Upper East Bay should be conducted in the fall to avoid fish spawning. Treatment should not be conducted in the summer (alum can get caught up with algae and float on the surface). In order to maintain adequate pH in the lake during alum treatment, the prescribed alum dose should be split into two doses and applied in subsequent years (i.e., fall 2008 and fall 2009).

Alum treatment of the East and Upper East Bay will lead to significant improvement in the phosphorus levels and the water clarity of the South Bay and the South-South Bay. This is because there are significant inflows to the South Bay from the East and Upper East Bays, and the level of phosphorus in water from the East Bay has a significant effect on the level of phosphorus in the South Bay. Modeling performed as part of this study confirmed this. The primary benefit of treating the sediment of the South Bay with alum is the reduction of internal loading in the winter as well as the summer. Alum treatment will significantly reduce the level of phosphorus in the spring after turnover of the lake (spring mixing) because phosphorus levels will not have built up on the bottom of the lake during the winter months. This will lead to reduced spring to early June algal blooms. Also, the alum treatment will reduce the degree and frequency of algal blooms in late August. If the alum treatment is not conducted, low phosphorus levels from the East Bay will have the effect of reducing phosphorus levels in the South Bay throughout the year. The potential benefit of also treating the South Bay (described above and in Table Ex-1) will need to be evaluated against the expected additional cost of treatment.

5.0 References

Barr Engineering, 2007. Alum Treatment Facility Feasibility Study for Muskellunge Creek.

Håkansson L. and M. Jansson. 1983. Principles of Lake sedimentology. Springer-Verlag, Berlin, 316pp.

Pilgrim, K.M., B.J. Huser and P.L. Brezonik. 2007. A method for comparative evaluation of whole-lake and inflow alum treatment. Water Research. 41: 1215-1224.

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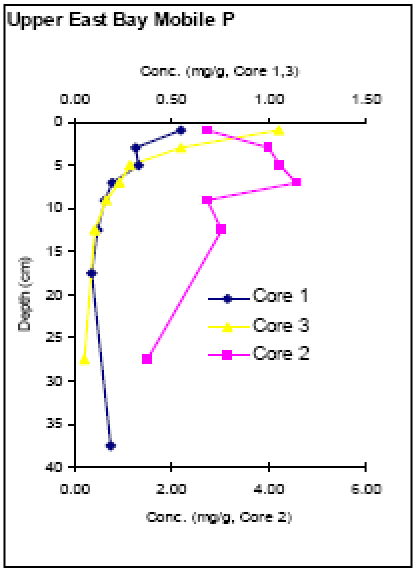
Psenner, R., B. Boström, M. Dinka., K. Pettersson, R. Puckso and M. Sager. 1988. Fractionation of phosphorus in suspended matter and sediment. Arch. Hydrobiol. Suppl. 30: 98-103.

Figures

Figure 1. Mobile sediment phosphorus in the North Bay sections (Upper East and East Bays).



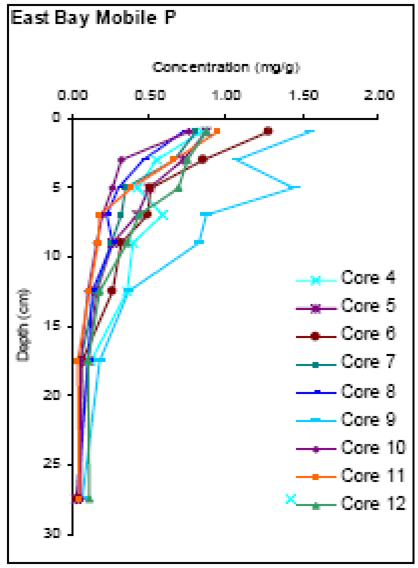
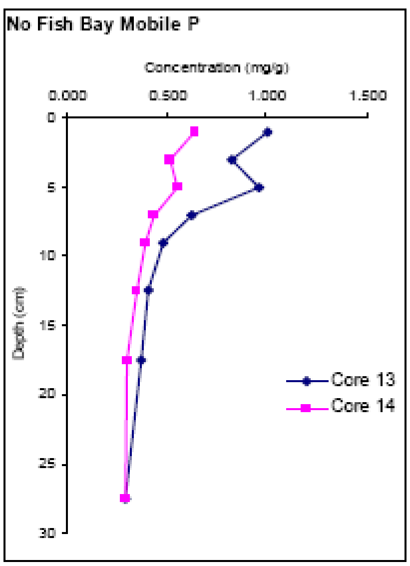


Figure 2. Mobile sediment phosphorus in the No Fish and West Bays.



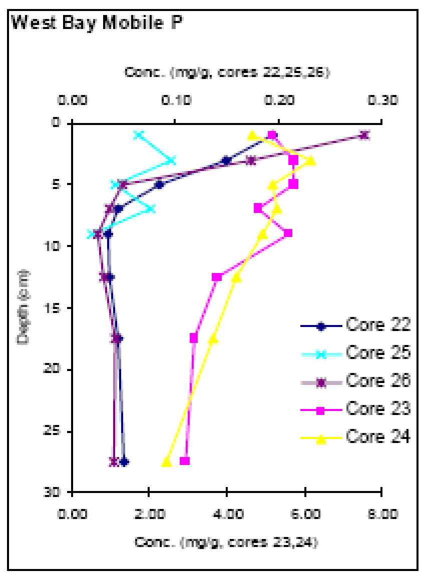


Figure 3. Mobile sediment phosphorus in the South and Second South bays.

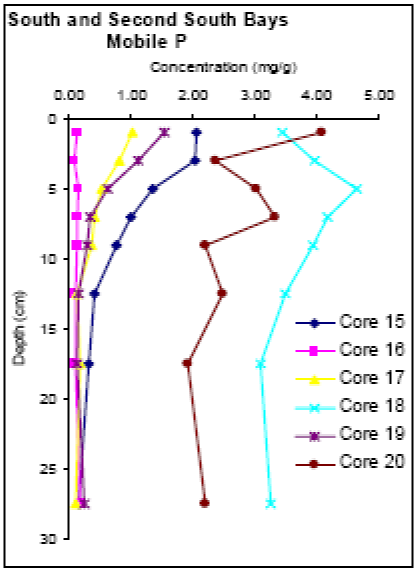
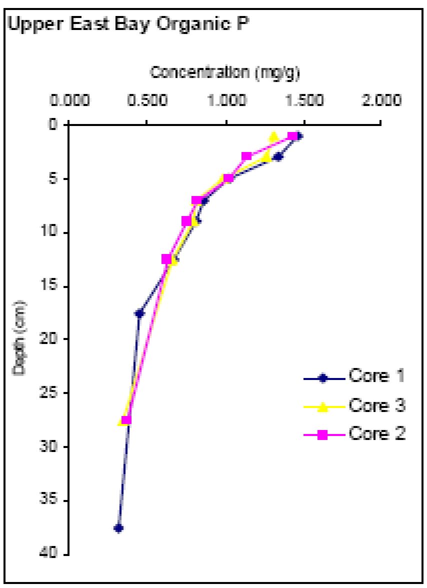


Figure 4. Organic sediment phosphorus in the North Bay section (Upper East and East Bays).



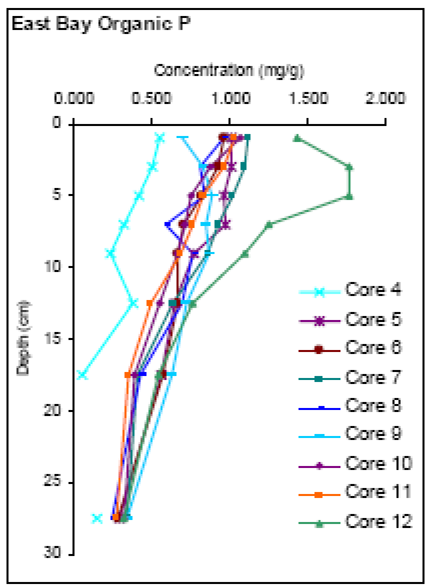
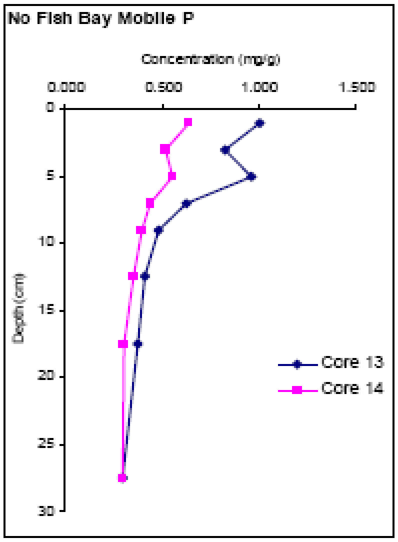


Figure 5. Organic sediment phosphorus in the No Fish and West Bays.



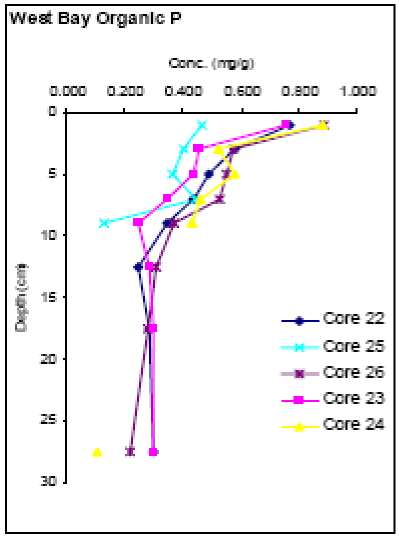


Figure 6. Organic sediment phosphorus in the South and Second South bays.

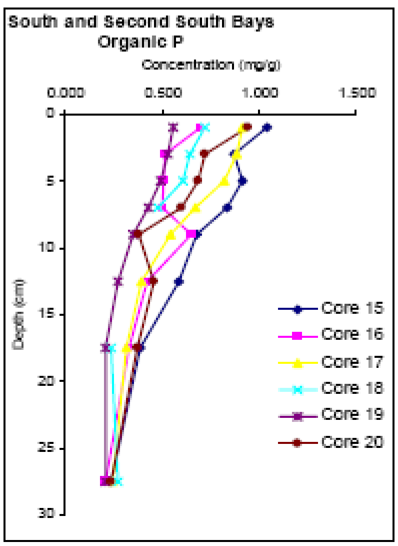
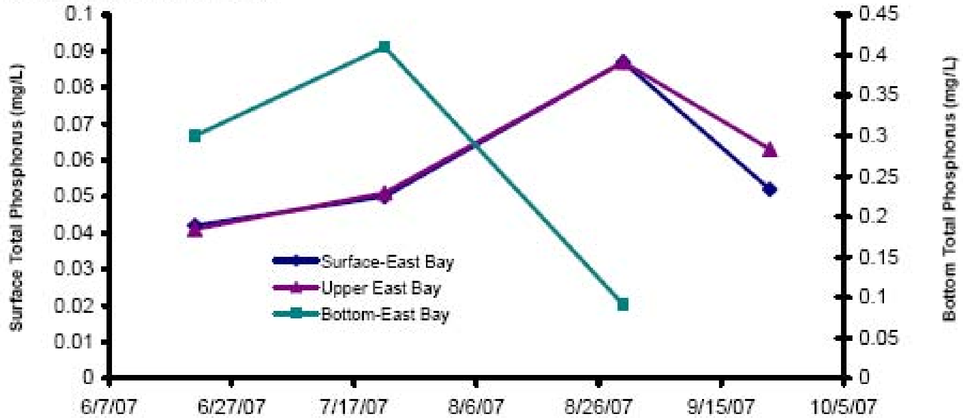
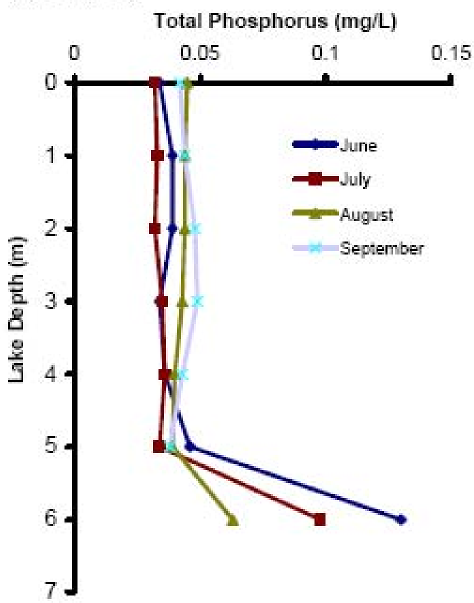


Figure 7. Surface and Bottom Total Phosphorus in the East and Upper East Bay (a), the South Bay (b), and the West Bay (c) in 2007.

(a) East and Upper East Bay



(b) South Bay



(C) West Bay

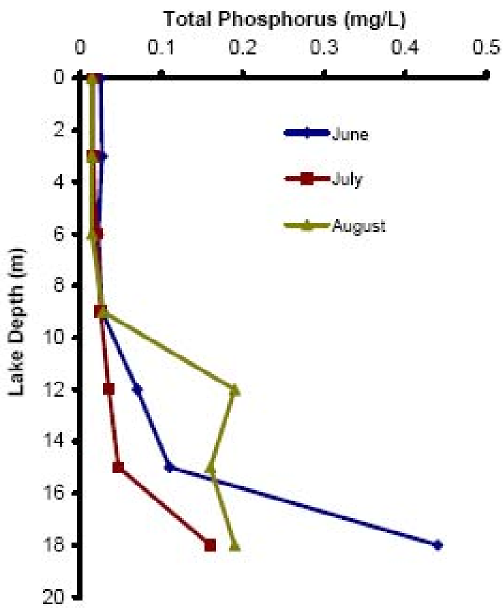


Figure 8. Calibration results for the Muskellunge Creek watershed yield model. Results are shown as cumulative average daily flows (a) and average daily flows (b).

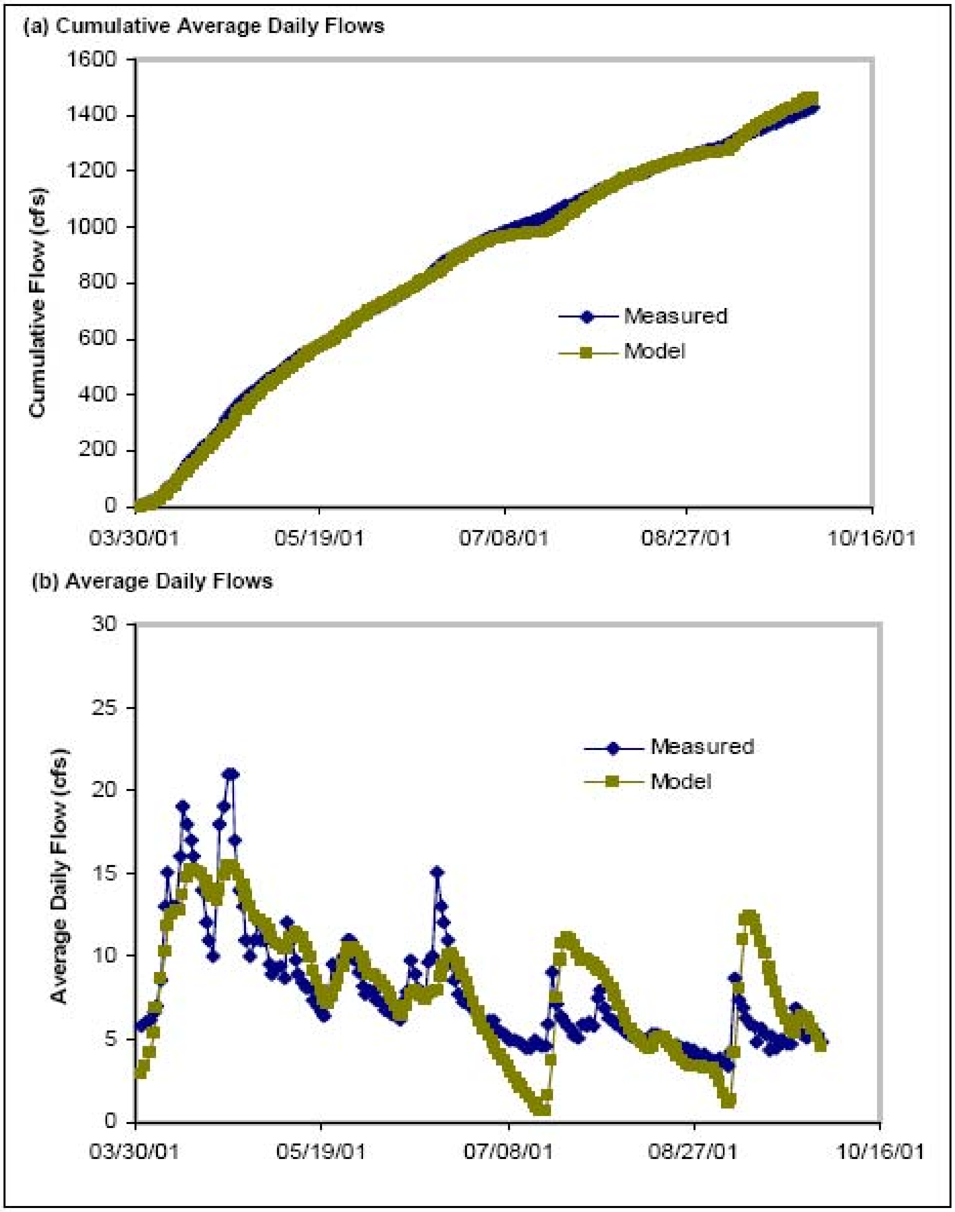


Figure 9. East Bay water quality model calibration (a,b,c) and the expected total phosphorus concentration in the East Bay (d) with alum treatment.

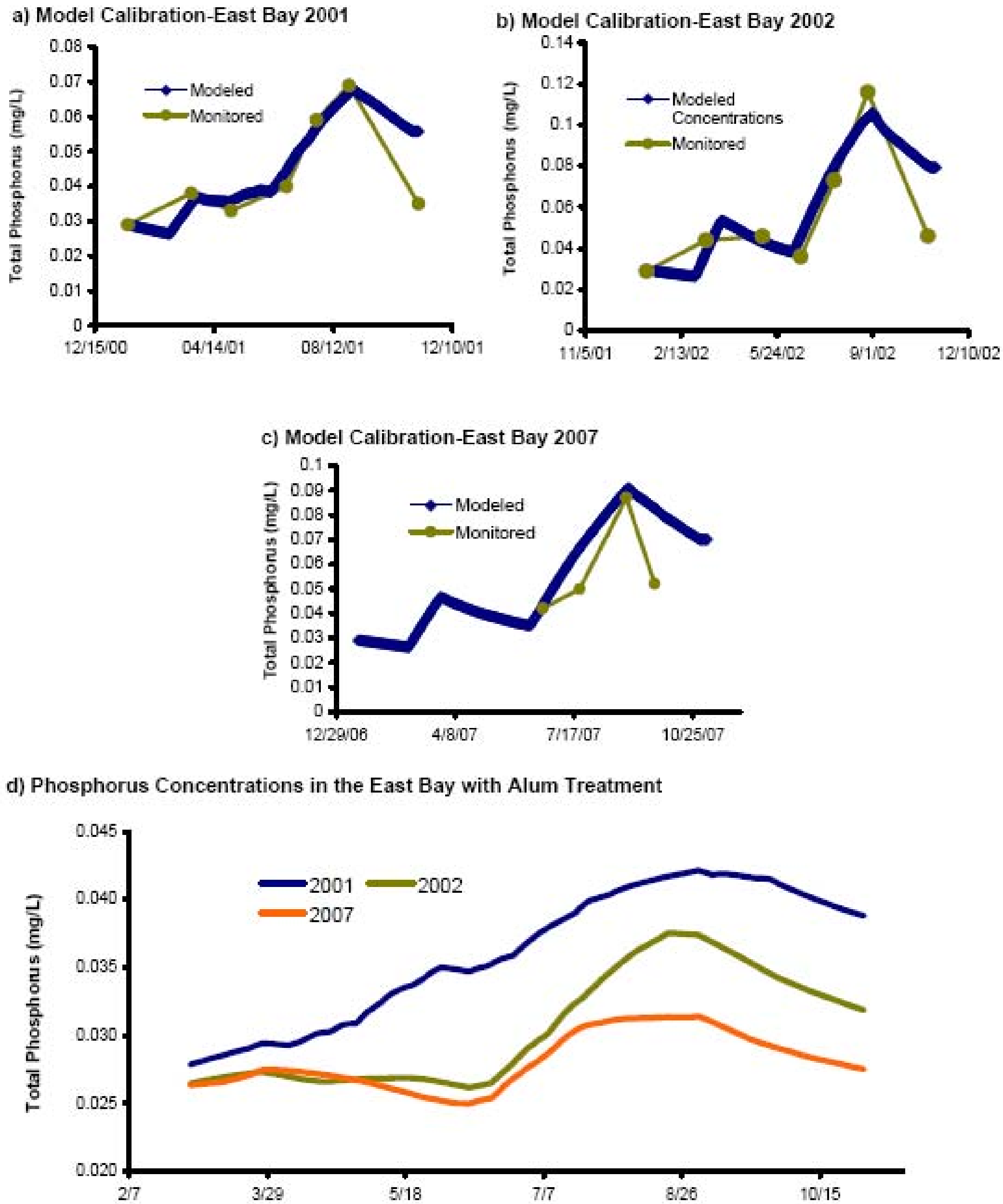
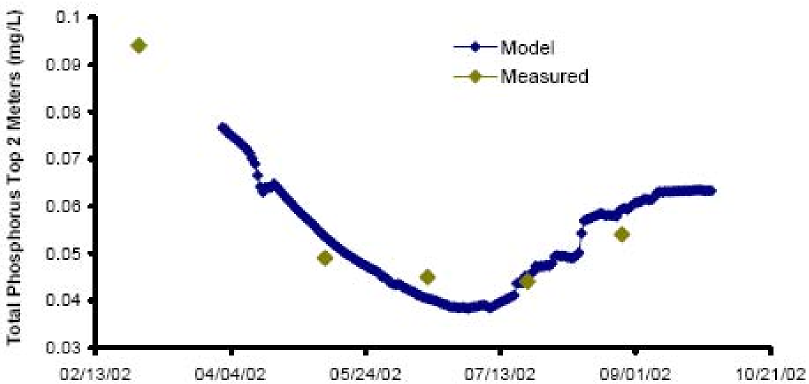


Figure 10. Model calibration results for the South Bay (a) and the effect of internal load reduction (alum treatment) in the East Bay and the South Bay on South Bay total phosphorus concentrations.

(a) Results of Model Calibration for the South Bay



(B) South Bay Total Phosphorus Concentrations with Various Alum Treatment Regimens

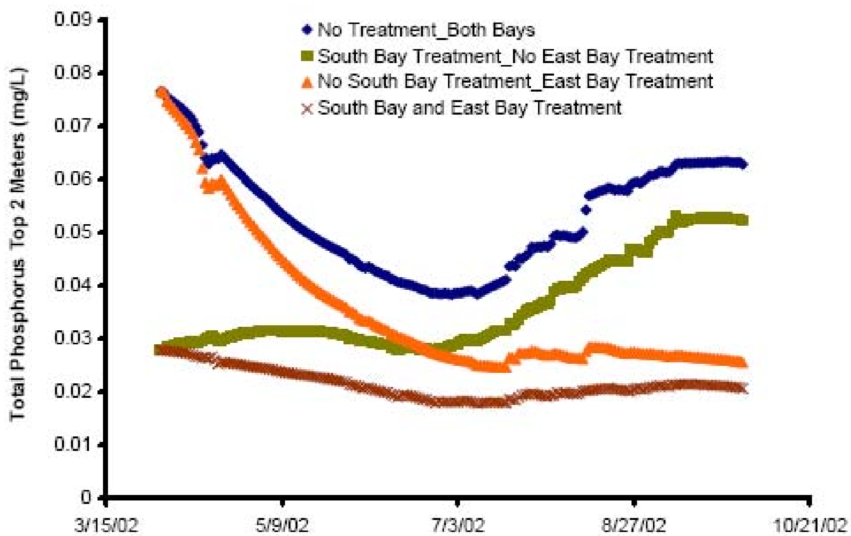


Figure 11. Modeled Temperature in the South Bay in 2001

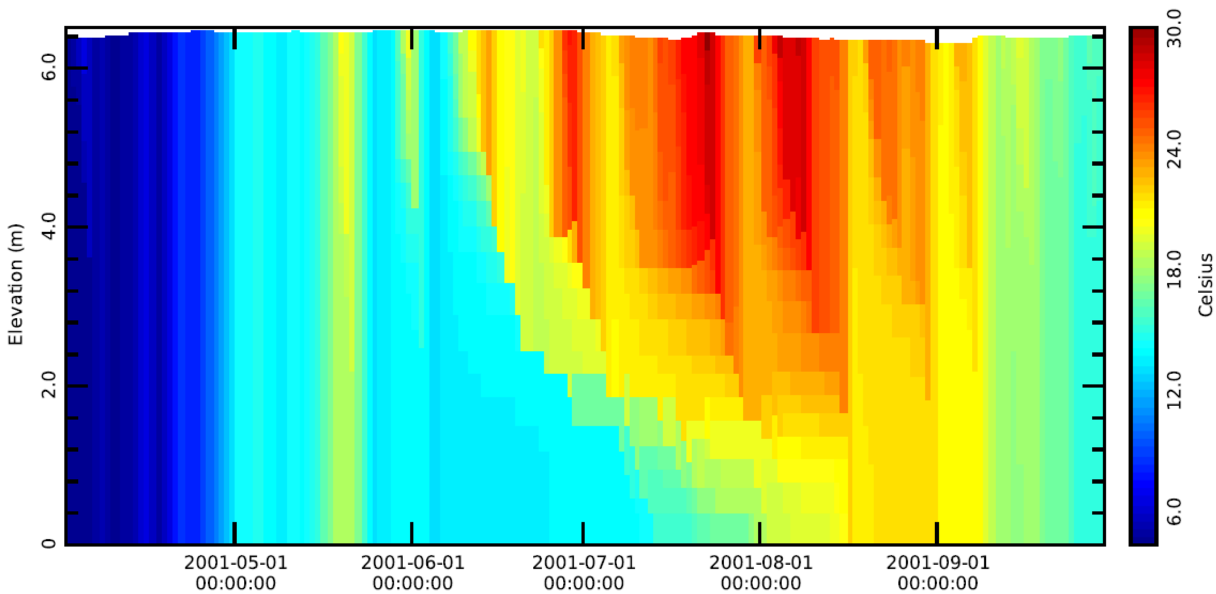


Figure 12. Modeled Dissolved Oxygen in the South Bay in 2001.

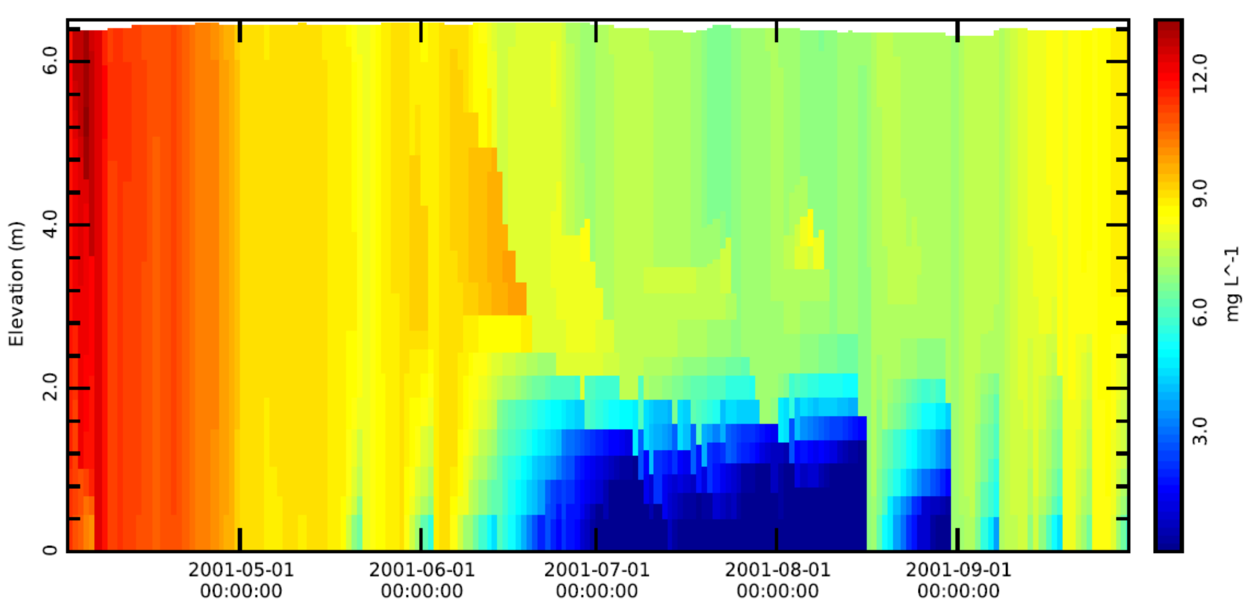


Figure 13. Modeled Total Phosphorus in the South Bay in 2001.

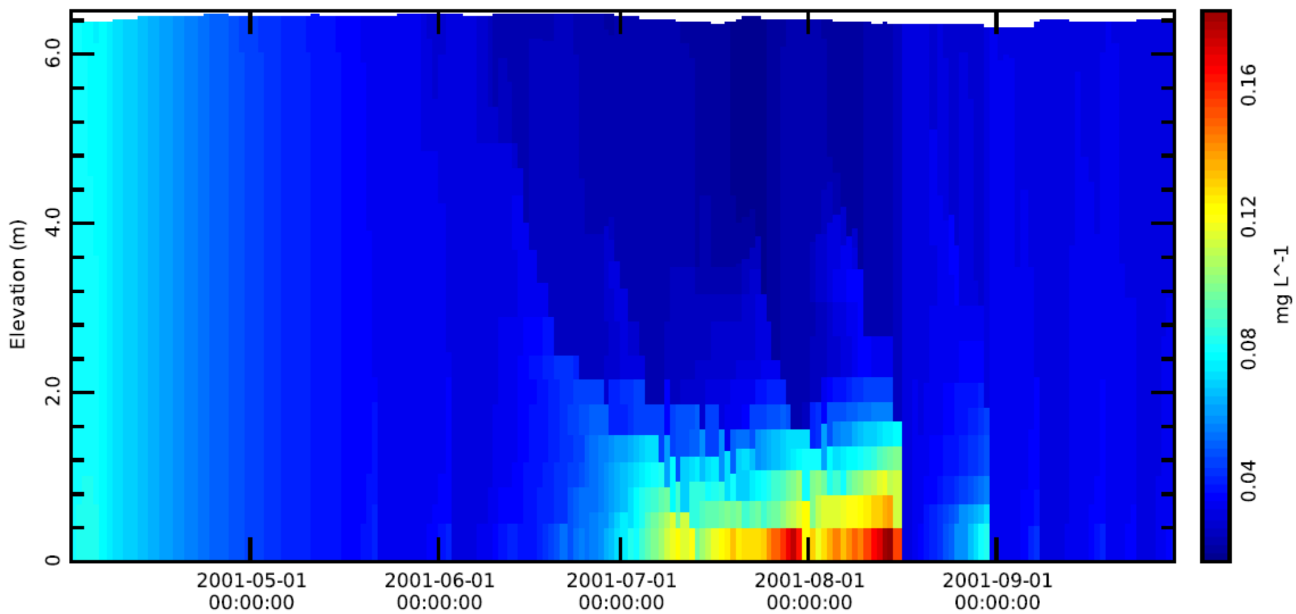


Figure 14. Comparison of measured and modeled temperature in the South Bay in 2002.

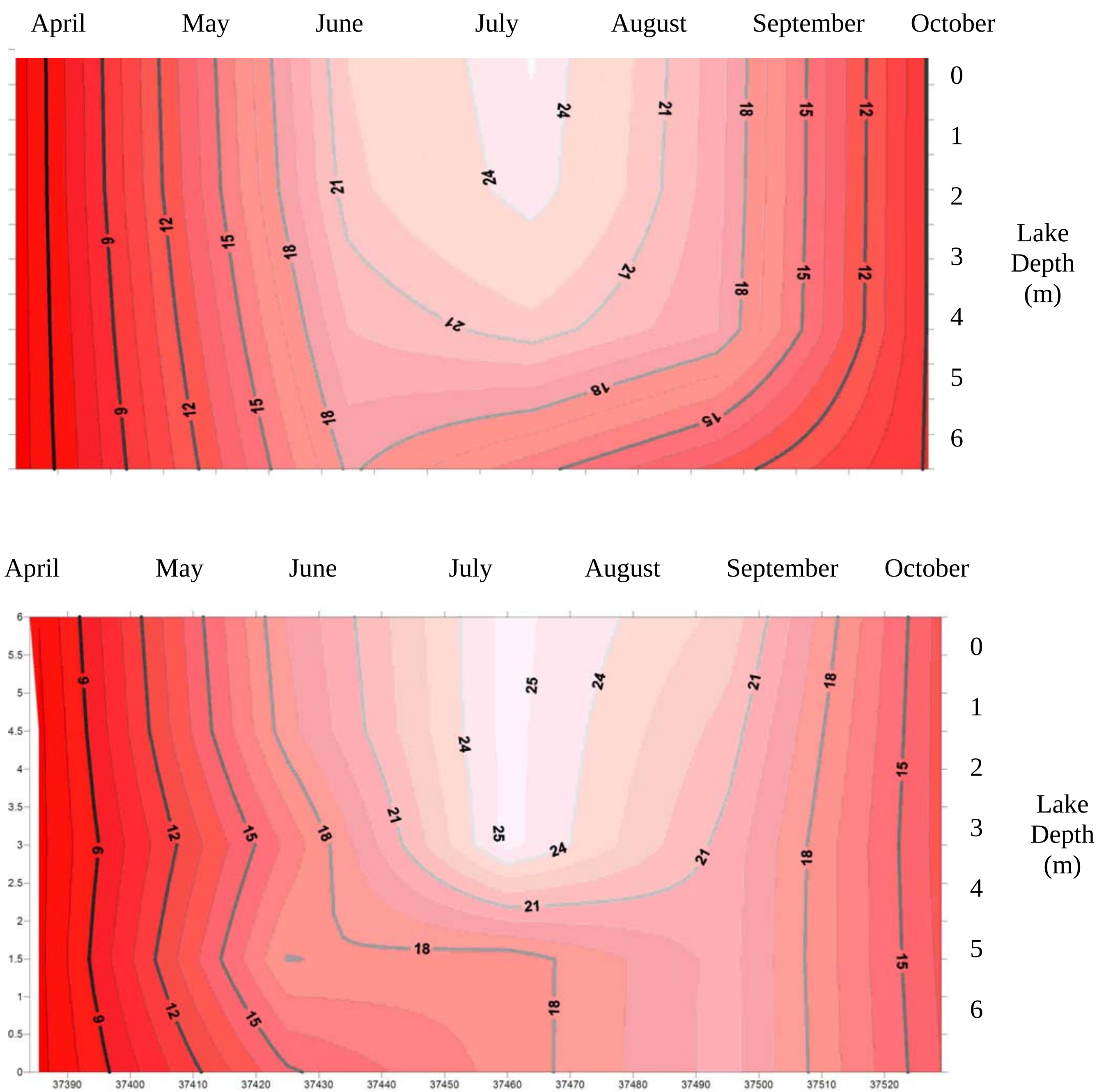


Figure 15. Dissolved Oxygen in the South Bay in 2002.

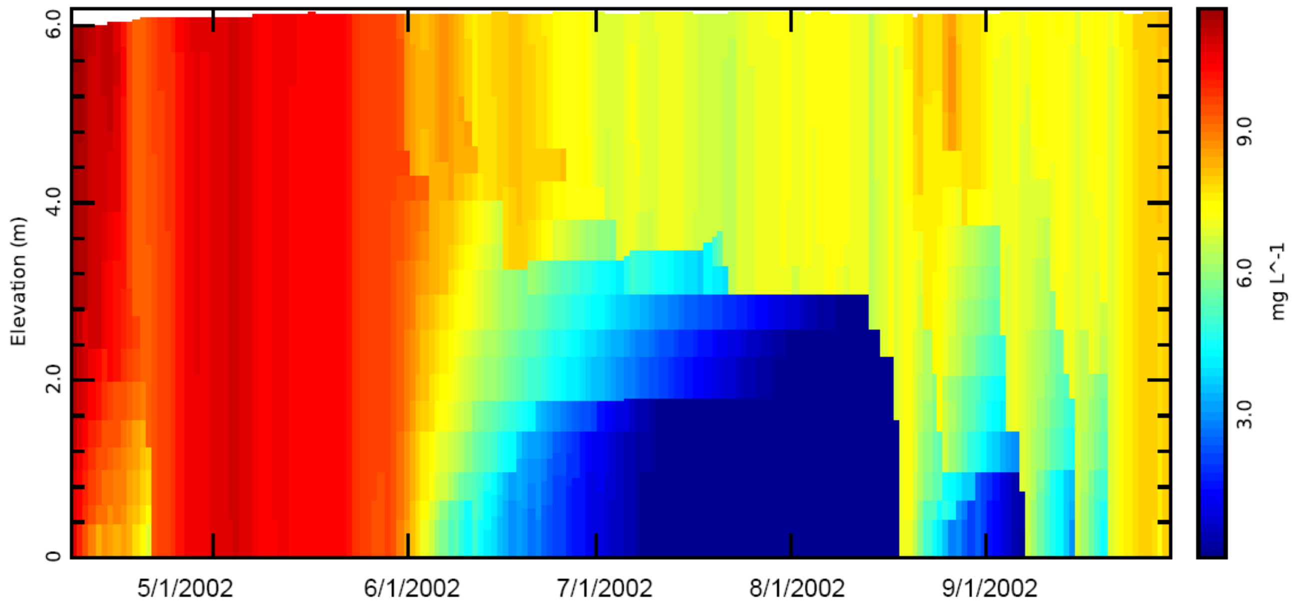


Figure 16. Total Phosphrous in the South Bay in 2002.

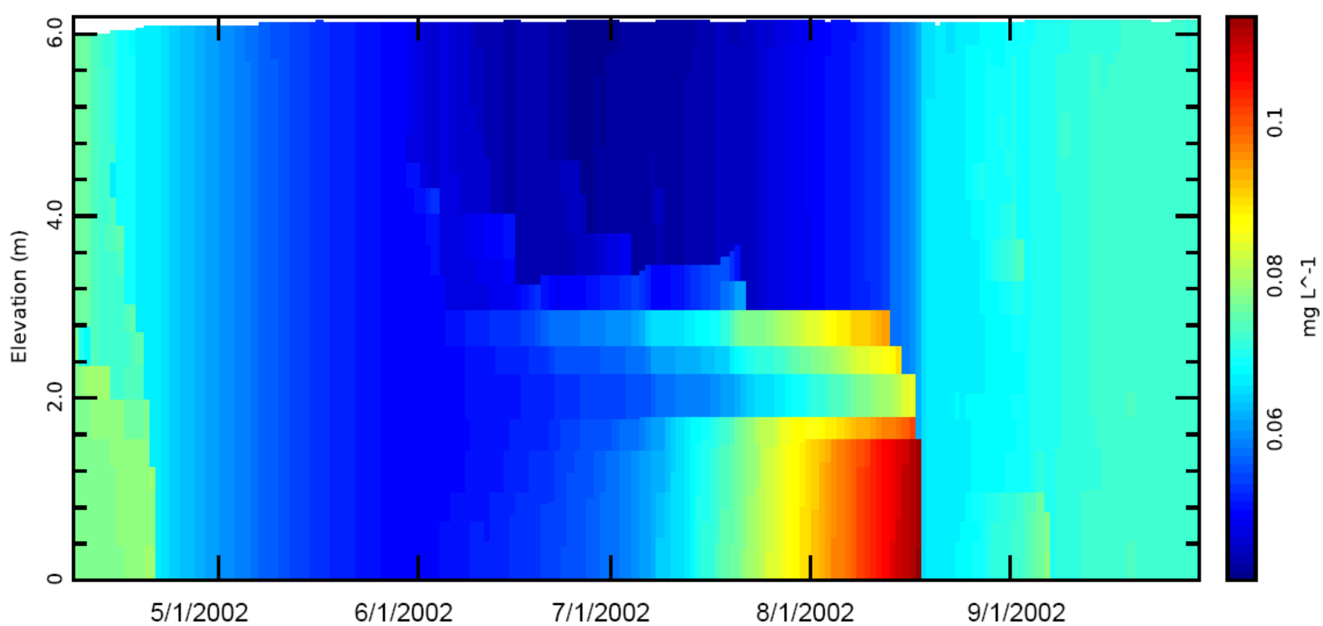


Figure 17. Relationship between total phosphorus and Secchi disc depth and chlorophyll a in the South Bay (a,c) and the East Bay (b,d).