

Final Report

NYSGLPF Grant C302396

**Impact of Anoxia and Alum on the Phosphorus Cycling from Internal Loads in
Irondequoit Bay, Rochester Embayment Area of Concern.**

Prepared by

Mark R. Noll
and
Joseph C. Makarewicz

Abstract

Irondequoit Bay has exhibited degraded conditions since the early 1900s. Considerable effort and funds to reduce phosphorus loading into the Bay has occurred including removal of treated sewage effluent emptying into the bay watershed, control of losses of phosphorus from the watershed, alum treatment of the deep sediments, and finally restoration of oxic conditions by addition of atmospheric air to the hypolimnion. A dialog has begun between the New York State Department of Environmental Conservation and the Monroe County Health Department on the appropriate next step. The focus of the dialog is selection of the appropriate technology, oxygenation or additional alum treatment, to maintain gains in water quality and ecosystem health. The ultimate goal of this project is determine quantitatively the rate of release of phosphorus from the deep sediments of Irondequoit Bay by microcosms and modeling to help direct the next step of the restoration of Irondequoit Bay. In addition, the proposed project will investigate geochemical processes in the sediment that influence water quality and ultimately ecosystem health to develop models that might be used to better predict changes in water quality with changes in management strategies.

Background

Lake sediments serve as sinks, sources, and transformers of nutrients and other chemical contaminants, and as such they can have a significant impact on water quality and ecosystem productivity. The ecosystem biogeochemistry, which includes chemical, biological and physical processes in the sediment and water column is the primary force for change. Often, these processes are ignored and the ecosystem is treated as a 'black box' using a simplified input-output analysis to address water quality issues. This traditional empirical approach may be inadequate for effective evaluation and management of an ecosystem.

Phosphorus cycling in lakes may be strongly influenced by the release of sediment bound P during periods of anoxia. Phosphorus has a strong affinity for sorption onto surfaces of iron (Fe) (and manganese (Mn)) oxyhydroxide phases. The P associated with these phases is subject to changes in redox conditions. Therefore, during periods of anoxia, P which is sorbed to these phases may be released into solution as the oxyhydroxides dissolve. As waters become oxygenated following a mixing event, the Fe (Mn) oxyhydroxides re-precipitate and scavenge P from solution. The mass of P associated with the sediment, and possibly subject to redox induced cycling, is termed the internal load (L_{int}).

Nurnberg (1998) has developed and tested models to estimate the total P and trophic state of lakes. The models use a mass balance approach requiring prior knowledge of both internal and external P loading rates, L_{int} and L_{ext} , respectively. In stratified lakes with oxic hypolimnia, L_{int} may be considered absent. This assumes that the only flux of P from the sediment is due to its release during anoxic periods. In

stratified lakes with anoxic hypolimnia, L_{int} is an important contributor to the annual P budget. L_{int} may be determined from experimentally derived P release rates from sediment surfaces and a measure of anoxia at the sediment surface in days per year (Nurnberg, 1995). Nurnberg (1987) found that L_{int} correlates with hypolimnetic P increases during summer anoxic periods. Furthermore, Nurnberg (1984) used L_{int} to predict annual whole lake average P values. Nurnberg (1991) investigated the contribution of L_{int} to the annual P budgets for the portions of the Great Lakes and surrounding smaller lakes. This study concluded that processes at the water-sediment interface and changes in upper sediment layers combined with an understanding of external P inputs are critical to assessing annual P budgets as the sediment may constitute both a source and sink for P.

Sediment iron (Fe), and to a lesser extent manganese (Mn), contributes to the cycling of P. Nurnberg and Manning (1991) investigated the relationship between sediment P and Fe(Mn). In their study, sediment cores were incubated to simulate anoxic conditions. The concentrations of water and sediment P and Fe were determined at different time intervals. Their findings support the theory that high P in anoxic hypolimnia is linked to the dissolution of sediment Fe oxyhydroxides and that upward migration of P and Fe in the sediment column provides a long-term source.

Phosphorus may also be released by microbial activity (Gachter and Meyer, 1993) at the sediment surface. Correlation of P and Fe concentrations in sediment and water provides an indication as to the relative importance of anoxic reduction and microbial P release.

Alum is commonly used to reduce lake P levels and minimize internal loading from the sediment. Welch and Cooke (1999) summarize the results of alum treatment on 21 lakes across the United States. For dimictic lakes, the effectiveness/longevity of alum treatment to reduce internal loading is expected to be approximately 15 years. A decline in effectiveness over time may be linked to several factors including bioturbation or burial of the aluminum floc layer. Relationships were evident between treatment dose and longevity, as well as treatment dose and sediment P release rates.

Irondequoit Bay has exhibited degraded conditions since the early 1900s (Bannister and Bubeck, 1978). In 1968, Monroe County initiated a plan for pollution abatement called the Pure Waters Master Plan. This plan directed that wastewater effluents discharged into the Bay and surrounding watershed be diverted to the Van Lare sewage treatment plant. Total phosphorus (P) loads were reduced from 298 kg TP/day to 60 kg TP/day (Bannister and Burton, 1979; Taddiken, 1985). In the early 1980s, the Irondequoit Basin Framework Plan was developed by Monroe County using data from the Nationwide Urban Runoff Program (NURP) to establish stable mesotrophic conditions in the bay.

The Clean Lakes 314 program determined that internal P loading from sediment during periods of anoxia sustains eutrophic conditions even after external loading has been reduced or eliminated (Cole, 1983; EHL, 1991). An additional phase of this project (EHL, 1984) demonstrated that sediment sealing with alum is effective in reducing the release of P from sediments. In 1993, the Irondequoit Bay Oxygen Supplementation Project initiated large scale oxygen sparging into the bay. The goal of this plan was to further reduce P levels by maintaining oxic conditions in the metalimnion and

hypolimnion. This would reduce reductant soluble-P losses from the sediment and promote biological activity.

Results and Discussion

Water Column Sampling and Analyses

Water column samples were collected weekly from 11 June to 5 August 2003. Samples were taken at 1 m intervals throughout the water column. These samples were analyzed for total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved oxygen (DO), total iron (Fe) and total manganese (Mn).

Results show a progressive decrease in oxygen in the hypolimnion following summer thermal stratification. During the early season, as shown in Figure 1 for 11 June, the difference in DO is evident, but an oxidizing environment persists. The pattern changes throughout the season with decreasing DO levels in the hypolimnion.

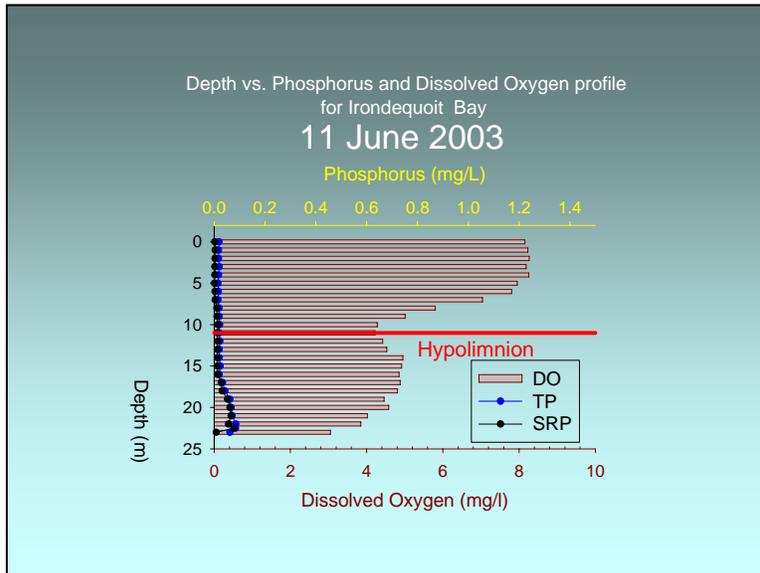


Figure 1. Summary diagram of the change in DO, TP and SRP with depth for 11 June 2003. Stratification is evident, but the hypolimnion remains oxic.

Figure 2 shows the result of the progression toward a low oxygen environment later in the summer stratification season. A true anoxic environment is not created due to the oxygenation program conducted by Monroe County. The low oxygen levels help limit the solubilization of phosphorus from the sediment by anoxic reduction of iron and manganese oxyhydroxides and their associated phosphorus.

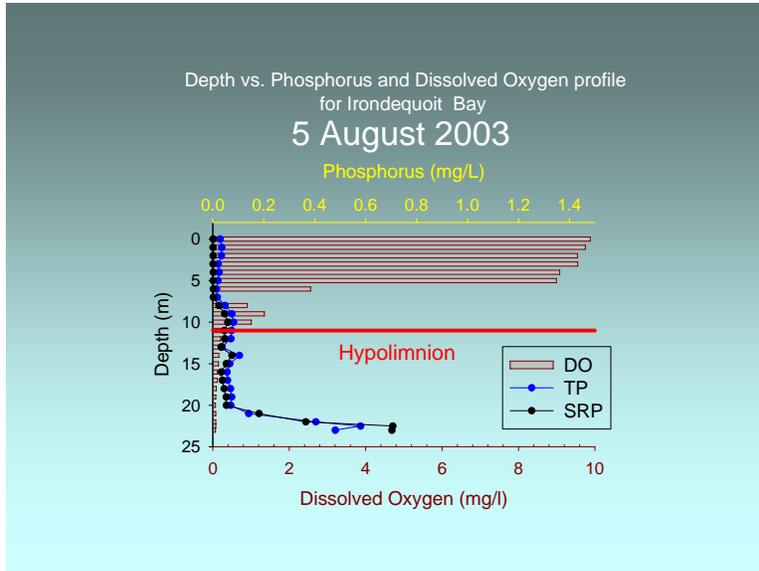


Figure 2. Summary diagram of the change in DO, TP and SRP with depth for 5 August 2003. Stratification remains throughout the summer season, but true anoxic conditions are not developed due to oxygenation of the hypolimnion.

Sampling during the 2004 summer season was changed to a monthly basis to obtain a snapshot of conditions throughout the summer until fall mixing. Sampling occurred approximately monthly from 19 May 2004 until 26 October 2004. Results indicate a similar pattern to the 2003 season with the progressive decrease in DO and increases in TP and SRP following the onset of summer stratification.

Figure 3 shows the profile from the 19 May 2004 sampling at the early onset of stratification. A hypolimnion is present, but is still well oxygenated. Additionally, TP and SRP concentrations are uniformly low throughout the water column.

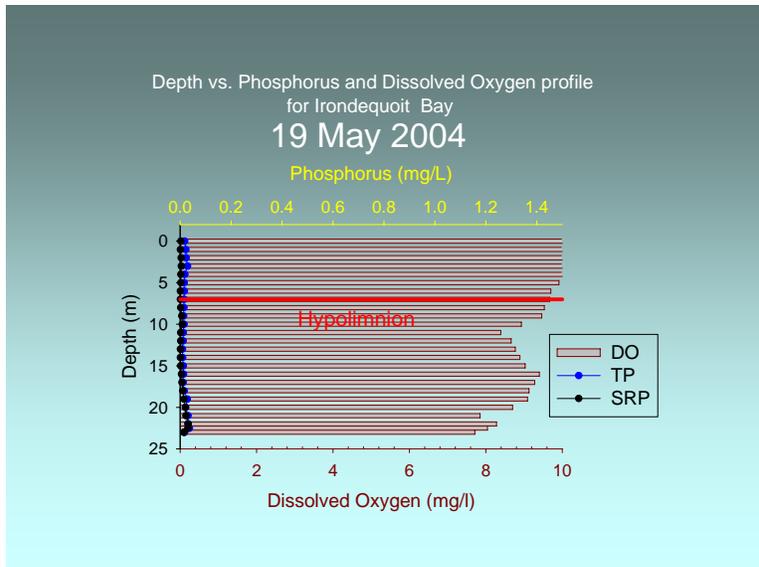


Figure 3. Summary diagram of the change in DO, TP and SRP with depth for 19 May 2004. Stratification is present, but the hypolimnion remains oxic.

Figure 4 shows the profile for 30 September 2004. Low oxygen conditions are present throughout the hypolimnion, but are maintained at levels generally in the 0.5 to 1 mg L⁻¹ range as a result of oxygenation. Concentrations below 0.5 mg L⁻¹ are present in the bottom 1 m of the water column. TP and SRP concentrations are elevated throughout the hypolimnion, typically in the range of 0.2 to 0.3 mg L⁻¹, but spiking up to 1 mg L⁻¹ as you approach the sediment-water interface.

A low oxygen zone was also observed in the metalimnion (Figure 4) with corresponding increased TP and SRP. It is postulated that this may be the result of the accumulation of organic debris at the thermal stratification boundary.

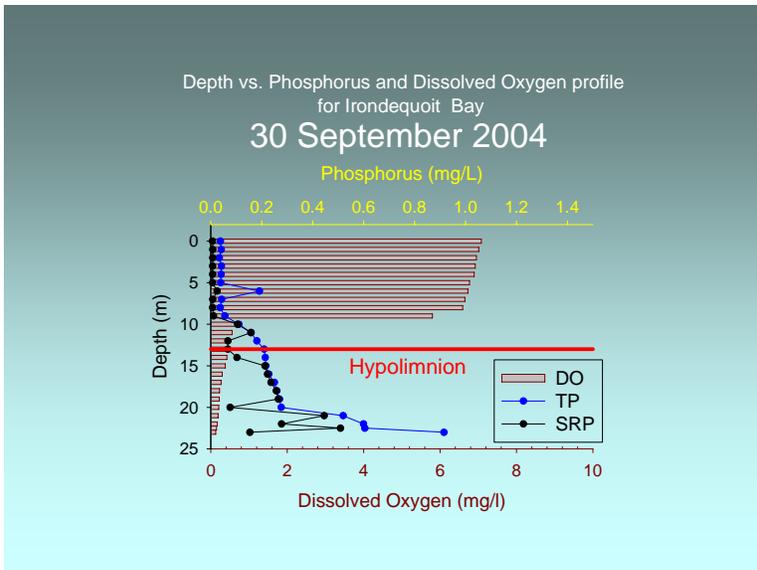


Figure 4. Summary diagram of the change in DO, TP and SRP with depth for 30 September 2004. Stratification remains throughout the summer season, but true anoxic conditions are not developed due to oxygenation of the hypolimnion.

Phosphorus release rates were determined for both the 2003 and 2004 season.

Figure 5 shows the continual increase in the mass of total P for the North Basin of

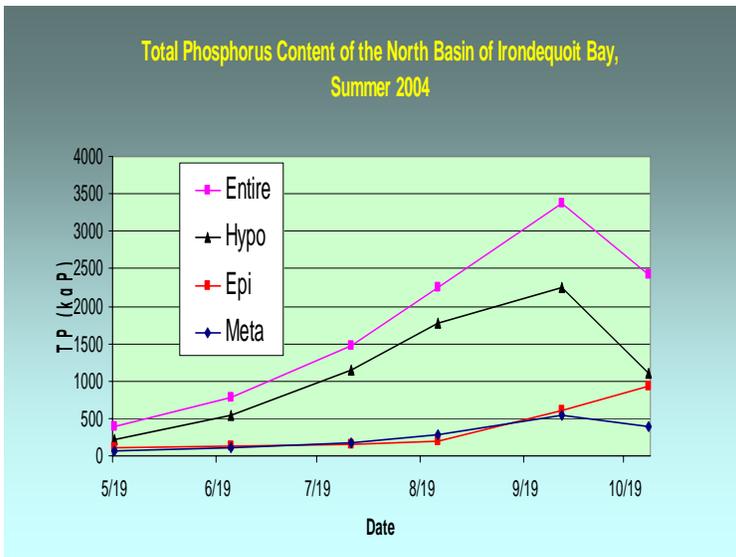


Figure 5. The mass of total P in the whole North Basin and three thermal stratification layers is shown for the 2004 season. Hypolimnetic TP increases steadily from the onset of stratification. Epilimnetic and metalimnetic TP remain nearly constant until late in the season when water column mixing begins to bring up some hypolimnetic waters to the surface layers.

Irondequoit Bay and the three distinct layers evident during summer thermal stratification. It may be assumed that the increase in TP in the hypolimnion is solely due to internal loading, while the epilimnion and metalimnion are likely dominated by external loading until late in the season when water column mixing begins.

Major ions in water samples collected during both the 2003 and 2004 seasons were determined by ICP-AES. Of particular interest, are the seasonal variations in the concentrations of Fe and Mn as their oxyhydroxides are sensitive to changes in redox conditions. As oxygen levels decrease due to summer thermal stratification and isolation of the hypolimnion, Fe and Mn oxyhydroxides are reduced and dissolved. The dissolution of the solid phase oxyhydroxides results in the release of associated P.

Figure 6 shows the progressive increase in water profile dissolved Fe and Mn throughout the summer thermal stratification period. Concentrations typically remain low in the epilimnion and metalimnion as a result of oxic conditions. In the hypolimnion, an increase in Fe and Mn concentrations is seen as stratification occurs. Higher concentrations of Fe are seen only in the lowest 2 m of the hypolimnion where anoxic conditions are likely to occur. Concentrations of Mn are seen to show an increasing trend through the entire summer season and throughout the hypolimnion. The higher redox potential of Mn oxyhydroxides allows for their dissolution in the low DO environment produced by the oxygenation program.

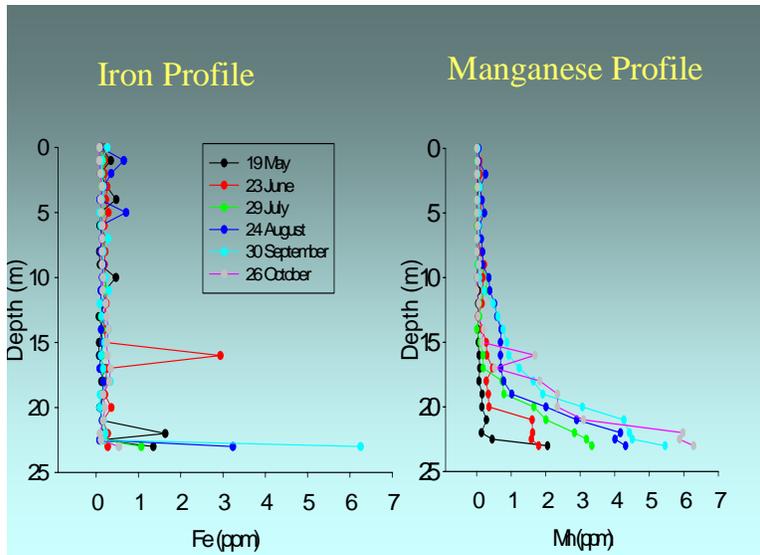


Figure 6. Profile of dissolved Fe and Mn concentrations for the summer 2004 season show a progressive increase in Mn concentrations in the hypolimnion with time. Fe concentrations show an increase later in the season and only in the lower 2 m of the water column.

As Fe and Mn oxyhydroxides are known to play a significant role in internal P loading, a correlation between Fe-P and Mn-P is expected. Figure 7 shows the correlations between water column Fe and Mn with TP. Concentrations are expressed as molar equivalents to express the relationship between Fe and Mn oxyhydroxides and their sorbed or co-precipitated P. No correlation exist between Fe and P. The maintenance of low oxygen conditions within Irondequoit Bay prevent the dissolution of Fe oxyhydroxides and release of their associated P. A strong correlation exist between Mn and P. This highlights the importance of Mn dissolution, which may occur at low DO concentrations, in the cycling of P in Irondequoit Bay.

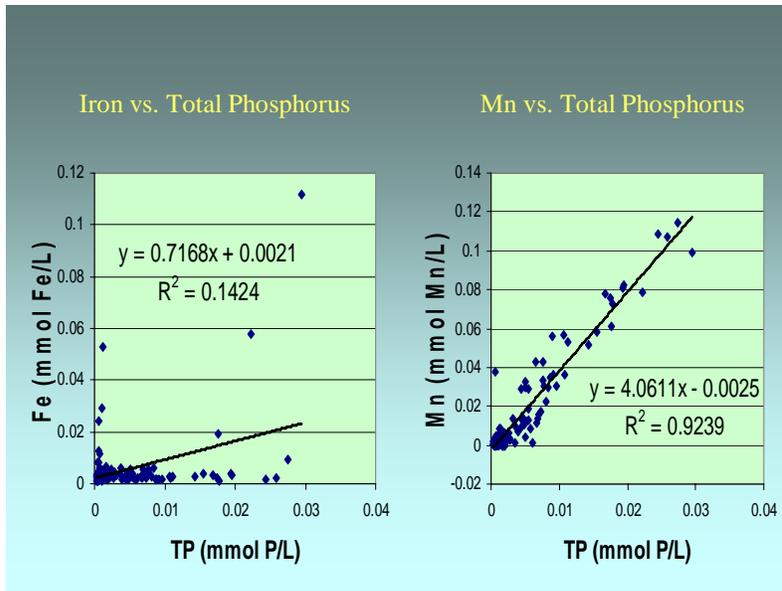


Figure 7. Correlations between dissolved Fe and Mn in the water column with TP show no relationship between Fe and P but a strong relationship between Mn and P.

Sediment Sampling and Analyses

Core samples were collected from three locations in May 2003 to be used for sediment incubation studies. Additionally, grab samples of sediment were collected at the location of water profile sampling during each water sampling event. Results during the 2003 season indicated that core samples should be collected at each water sampling event. During the 2004 season, core samples were collected approximately monthly along with water samples.

The 2004 core samples were frozen and segmented into sections ranging from 2 to 5 cm length. The segments were analyzed for total extractable metal and P. Figures 8 through 11 show results for P, Fe, Mn and Al, respectively. Sediment P shows a spike in concentration at approximately 20 cm depth. This correlates with an Al spike and indicates the location of the “alum layer”. This layer, now consisting of aluminum oxyhydroxides and co-precipitated P, is visible in most cores. The depth of the layer

ranges from about 18.5 cm to 21 cm depth. In some cores, the layer is more diffuse and not visible, or may be deeper than the 25 cm sampled. Sediment Fe and Mn show varying patterns seasonally with spikes near the surface in May and again in September. This may indicate anoxic conditions within the sediment allowing for Fe and Mn redistribution or diffusion into the water column. Note that Fe concentrations in the sediment are approximately 10 to 20 times the Mn concentration.

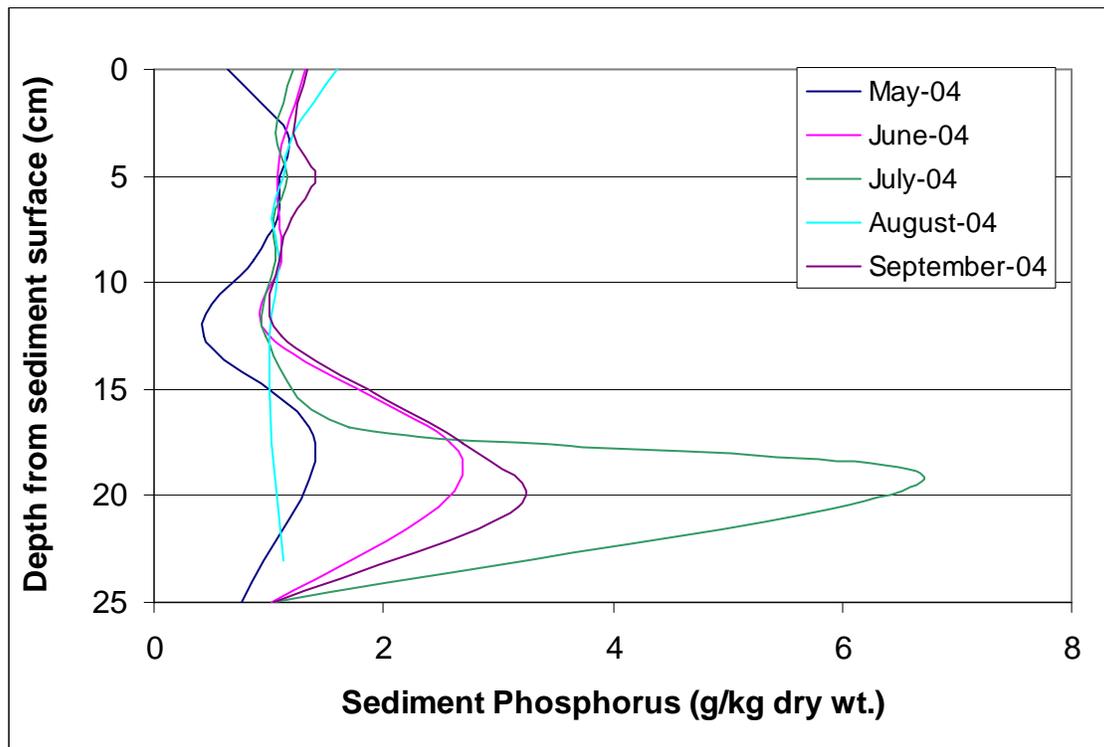


Figure 8. Sediment phosphorus profiles for sediment cores taken from the North Bay site of Irondequoit Bay during the summer of 2004.

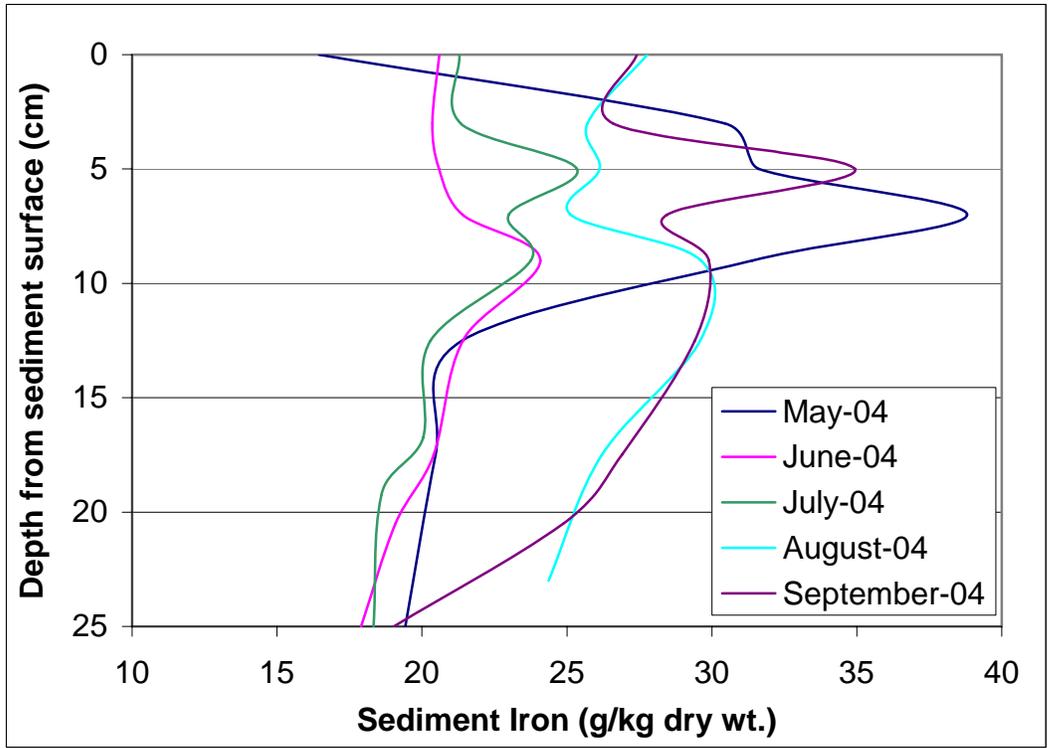


Figure 9. Sediment iron profiles for sediment cores taken from the North Bay site of Irondequoit Bay during the summer of 2004.

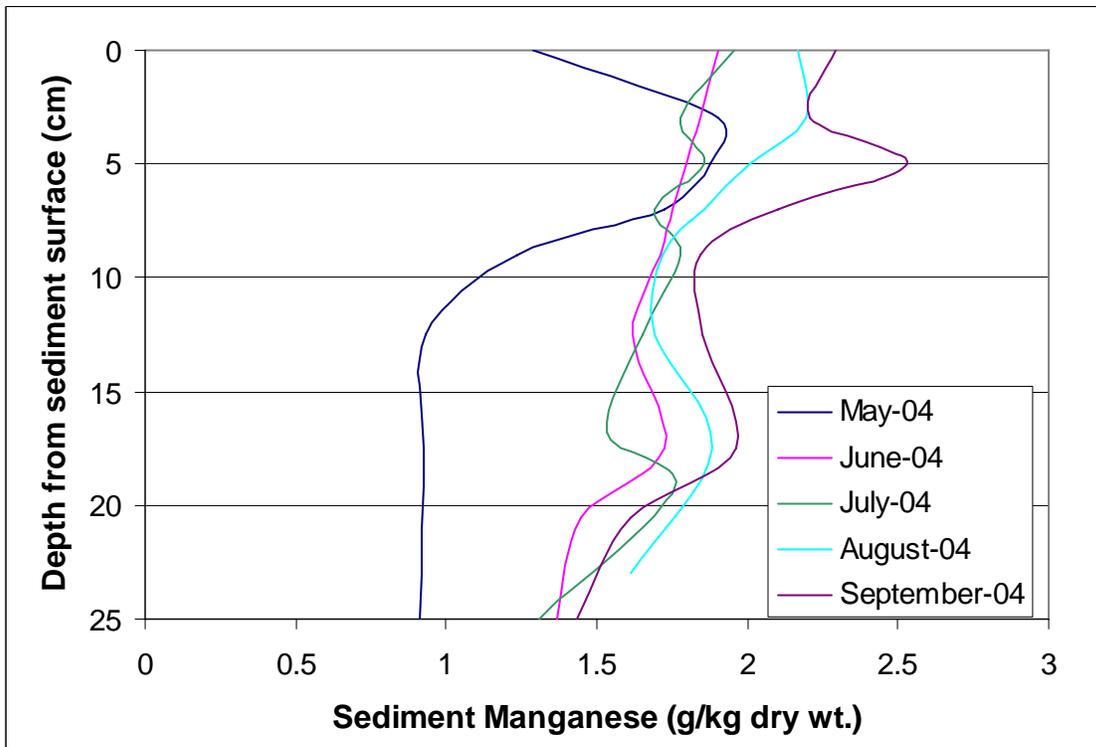


Figure 10. Sediment manganese profiles for sediment cores taken from the North Bay site of Irondequoit Bay during the summer of 2004.

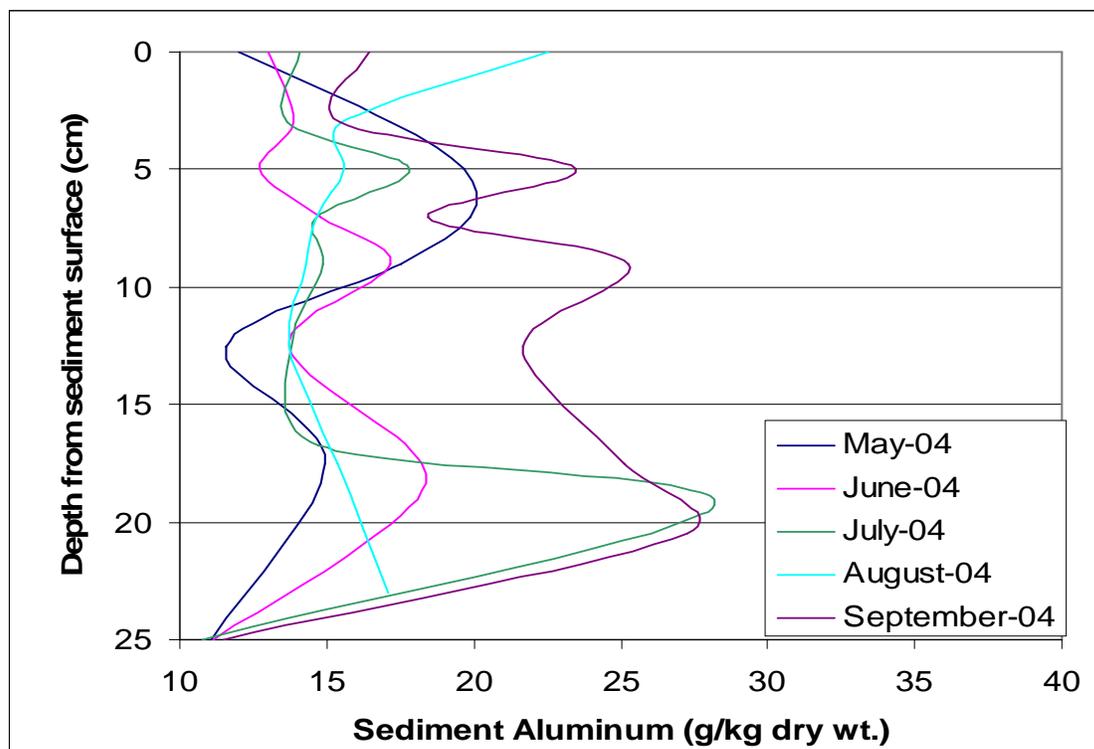


Figure 11. Sediment aluminum profiles for sediment cores taken from the North Bay site of Irondequoit Bay during the summer of 2004.

Sediment samples were also subjected to a sequential selective extraction procedure (Rydin, 2000) to elucidate the distribution of P among the various sediment physicochemical phases. Table 1 shows the sequence of extractions and the sediment phase each attacks.

Step 1	NaCl extractable - Solution and sorbed P
Step 2	NaOH extractable - SRP – Al bound P - NRP - Organically bound P
Step 3	Dithionite extractable - Fe and Mn oxyhydroxides bound P
Step 4	HCl extractable - Ca bound P

Table 1. Summary of steps in the P sequential selective extraction scheme. The extract in step 2 is analyzed for SRP to determine Al bound phosphate. The same extract is analyzed for TP with the difference between TP and SRP being non-reactive P (NRP).

Figure 12 shows the distribution of P among the various sediment phases for the July 2004 sediment core. Results are presented on a percent basis to show the relative distribution of P among the extracted phases. Total extracted P as a sum of each phase is similar to the total P determined by strong acid digestion of the sediment sample. Results for the July sample show the presence of the alum layer between 18.5 and 20 cm depth as indicated by the high NaOH-SRP extractable P. The NaCl extractable P accounts for a very small fraction of the total sediment P. This is expected as phosphate typically forms strong bond with various sediment phases. The sodium dithionite extractable P, or P associated with reducible phases, typically accounts for 35% to 50% of the sediment P. This is the fraction that is susceptible to cycling during anoxic periods. The HCl extractable P associated with Ca represents a relatively stable form of P within the sediment as long as pH values remain near neutral. Over time, this phase will account for an increasing percentage of the total sediment P. This may be observed in the 0-2 cm through the 10-15cm segments above the alum layer. As P associate with Fe and Mn oxyhydroxides and organic matter is cycled, P in solution within sediment pore spaces will preferentially associate or co-precipitate with Ca. The Al bound P is associated with naturally occurring aluminosilicates, or within the alum layer the Al oxyhydroxide or Al phosphate phases that formed at the time of application. The Al bound P is also a relatively stable form over long time periods. Figure 13 shows results from sequential extractions for the Summer 2004 season. The alum layer is evident in all but the August sample. Phosphorus associated with reducible phases (Fe and Mn) varies through the season, but still accounts for a high percentage of sediment P throughout the study period.

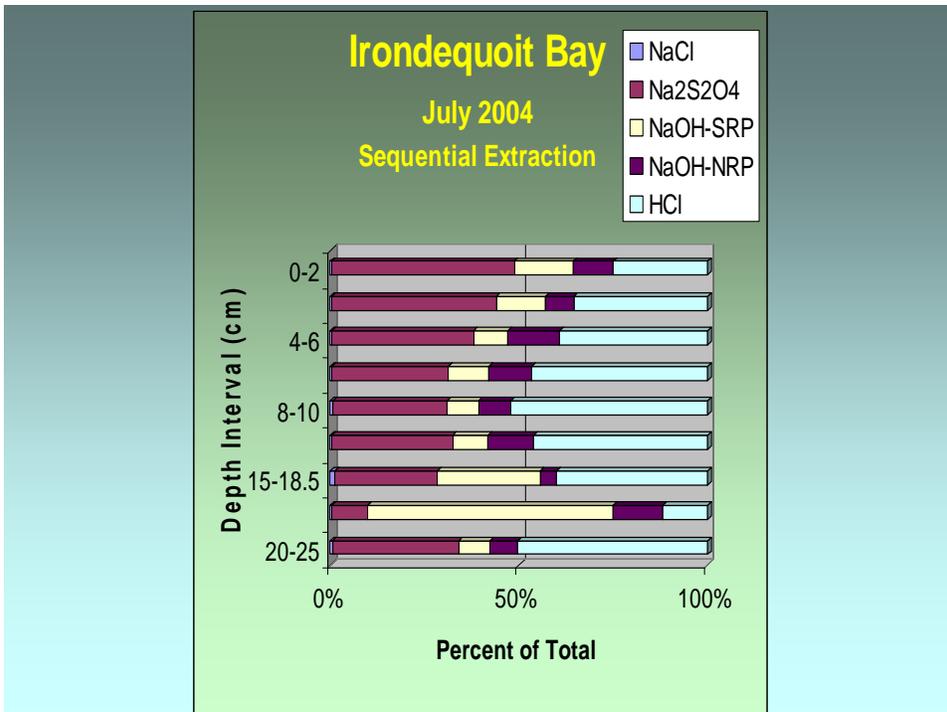


Figure 12. Distribution of P among the extractable phases within the sediment.

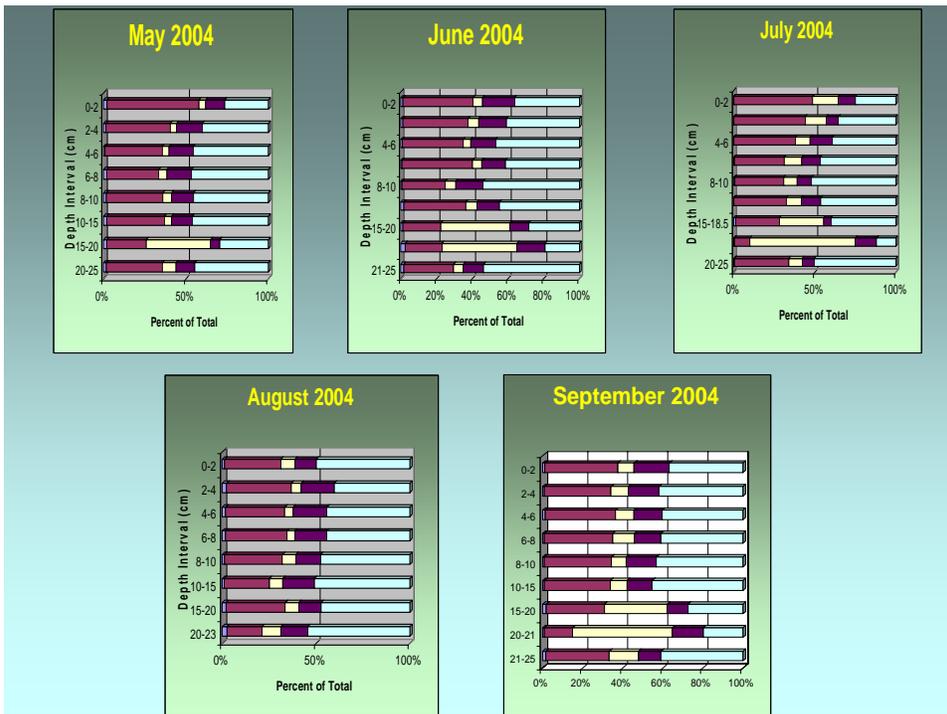


Figure 13. Distribution of P among the extractable phases within the sediment over time for the Summer 2004 season.

Release Rates

Sediment incubation studies were completed to evaluate the release rate of P from the sediment during imposed anoxic conditions. Intact sediment cores were used to conduct incubation studies. The cores were fitted with a manifold to support a water column above the sediment surface and enable sampling. Figure 14 shows the study underway.

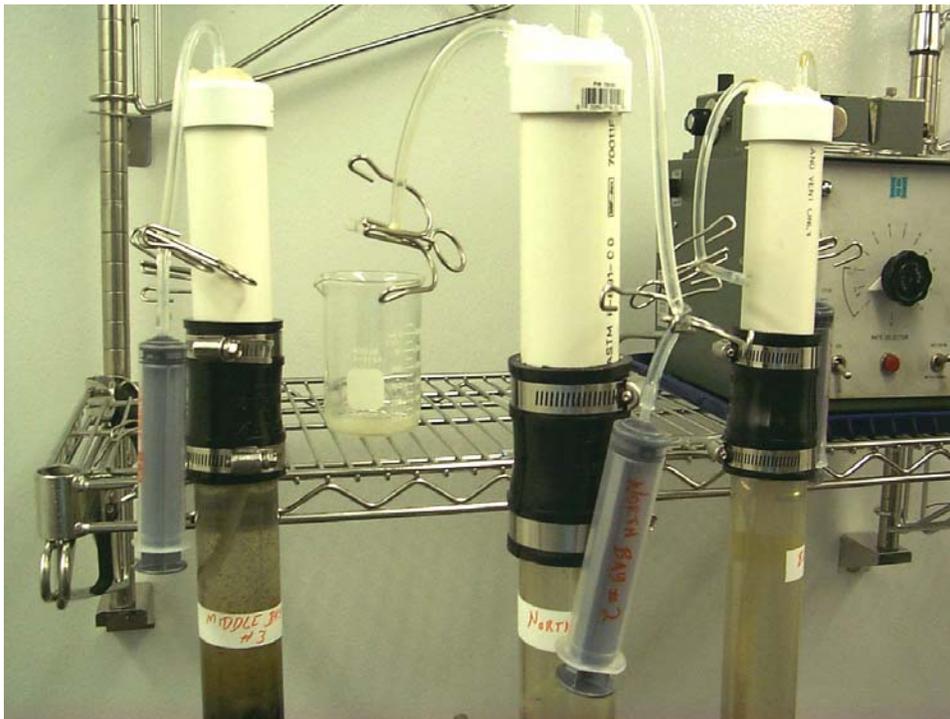


Figure 14. Sediment cores setup for incubation studies. Cores were kept in the dark and at 6°C to simulate bottom water conditions within Irondequoit Bay. Water used in the experiment was deoxygenated by N₂ purging and the addition of sodium sulfite.

Results of the incubation experiment show equivalent P release rates ranging from 2.12 to 3.77 mg P m⁻² day⁻¹ with an average of 2.89 mg P m⁻² day⁻¹. These release rates are comparable with existing models and field results for internal P loading.

Water column and sediment analyses were used to determine P release rates from the sediment into the water during summer thermal stratification and the development of low

oxygen conditions. Calculations were made using field data collected during the 2003 and 2004 field seasons and using various published models. Results are generally consistent, but field data indicates that models tend to under-predict observed rates.

Field data was used to calculate release rates for P within the North Basin of Irondequoit Bay. The North Basin represents the deepest part of the bay. Figure 15 shows the location of the North Basin and the 3 sediment core sampling locations collected in 2003. In 2004, sediment cores were only collected from the North Bay site. This site corresponds to Monroe County's site 1.



Figure 14. Map of Irondequoit Bay with sample sites located.

Table 2 shows results of release rate calculations for both the 2003 and 2004 seasons. The release rate for the 2003 season is lower than the 2004 season. This may be due to the shorter sampling time period during the 2003 season. Release rates within the hypolimnion are likely due to only internal loading processes. Release rates for the

epilimnion and metalimnion may be impacted by external P loading processes. The observed values of for internal loading produce an average of $8.15 \text{ mg P m}^{-2} \text{ day}^{-1}$. This is approximately 3 times the release rate determined from incubation studies.

Additional published models were used to evaluate internal P loading rates.

These models use various sediment data to estimate the P release rate during periods of anoxia produced by thermal stratification. The method of Ostrofsky et al. (1989) examines P release rates from lakes with high Fe-bound P and low organic P.

Irondequoit Bay is similar to the lakes in this study. Table 3 shows a comparison of key parameters used in calculating release rates. The Ostrofsky et al. model predicted a release rate of $2.98 \text{ mg P m}^{-2} \text{ day}^{-1}$ which compares well with our core incubation studies with an average of $2.89 \text{ mg P m}^{-2} \text{ day}^{-1}$.

Table 2. Loading Rates for Irondequoit Bay North Basin Bathymetric data for area and volume calculations taken from: Bannister, et al. (1982). Change and rate represent the change in phosphorus of the North Basin. Areal release rate calculated by dividing the rate of release (in mg/day) by the surface area of the North Basin of Irondequoit Bay.

11 June 2003 to 5 August 2003

	Change (kgP)	Rate (kgP/day)	Areal (mgP/m ² /day)
Epi	52.62	0.96	0.61
Meta	180.76	3.29	2.08
Hypo	586.64	10.67	6.75
Entire	820.01	14.91	9.44

19 May 2004 to 30 September 2004

	Change (kgP)	Rate (kgP/day)	Areal (mgP/m ² /day)
Epi	525.80	3.92	2.48
Meta	415.55	3.10	1.96
Hypo	2020.71	15.08	9.54
Entire	2979.80	22.24	14.07

North Basin Hypolimnion

Year	Change (kgP)	Rate (kgP/day)	Areal (mgP/m ² /day)
2003	586.6	10.67	6.75
2004	2020.7	15.08	9.54
	Mean	12.87	8.15

Table 3. Summary statistics for lake and sediment characteristics of 57 lakes examined by Ostrofsky *et. al.* (1989) and Irondequoit Bay. The values from Ostrofsky *et. al.* are from the top 2.5 cm of sediment. Irondequoit Bay values are the average of the top 2 cm of monthly sediment cores sampled at the North Bay site from May thru September 2004. Total phosphorus in $\mu\text{g/L}$, alkalinity in $\text{mg CaCO}_3/\text{L}$, all sedimentary phosphorus species in g P/kg sediment dry weight, sediment iron in g Fe/kg sediment dry weight, loss on ignition in percent of dry weight. $\text{NaOH-P}_{\text{metals}}$ includes redox sensitive and aluminum bound P; HCl-P is calcium bound P.

Parameter	Ostrofsky <i>et. al.</i> Mean (Range)	Irondequoit Bay Mean \pm S.E.
Total phosphorus	22 (5 - 111)	24.2 \pm 3.5*
Alkalinity	107 (11 - 287)	202.8 \pm 8.0**
Total sediment phosphorus	2.636 (1.342 - 9.212)	1.224 \pm 0.157
Organic sediment phosphorus	1.477 (0.677 - 2.520)	0.431 \pm 0.070
Inorganic sediment phosphorus	1.158 (0.308 - 7.325)	0.920 \pm 0.114
Loosely sorbed P	0.069 (0.000 - 0.872)	0.014 \pm 0.003
$\text{NaOH-P}_{\text{metals}}$	0.832 (0.188 - 5.879)	0.514 \pm 0.034***
HCl-P	0.258 (0.075 - 0.709)	0.391 \pm 0.099
Sediment Iron	46.547 (22 - 108)	22.705 \pm 2.161
Loss on ignition	27 (10 - 54)	10.1 \pm 0.3

* mean (n = 5) total phosphorus concentration from the surface of the North Bay site from May through September of 2004

** mean (n = 4) alkalinity concentration from the epilimnion of the North Bay site from June through September of 2004

***mean (n = 5) of the sums of the BD-P and NaOH-SRP fractions from sequential extraction analysis of sediments of the North Bay site from May through September of 2004

Nurnberg (1988) uses a predictive model to estimate internal P loading rates using total sediment P concentration, P associated with reducible phases from sequential extraction experiments and organic matter content as determined by loss on ignition.

Table 4 shows the results of model analysis of Irondequoit Bay data. The dry sediment model using total P and loss on ignition gives a release rate of $6.35 \text{ mg P m}^{-2} \text{ day}^{-1}$. This is similar to field observations of $8.15 \text{ mg P m}^{-2} \text{ day}^{-1}$.

Table 4. Phosphorus release rates (RR) resulting from applying Irondequoit Bay total sediment phosphorus (TP_s) and bicarbonate dithionite (BD-P) extractable phosphorus concentrations to the predictive regressions from Nürnberg (1988). Release rates are expressed in mg P/m²/day. Wet Sediment refers to regressions based off of phosphorus concentrations expressed as µg P/g wet weight and Dry Sediment refers to regressions based off of phosphorus concentration expressed as mg P/g dry weight. The Phosphorus Fraction column refers to the phosphorus fraction utilized by the regression to predict a release rate. TP_s – LOI refers to the regression of release rate and total sediment phosphorus with loss on ignition (LOI) as a second variable.

Phosphorus Fraction	Predicted RR Wet Sediment (mg P/m ² /day)	Predicted RR Dry Sediment (mg P/m ² /day)
TP _s	23.82	0.11
BD-P	31.56	4.22
TP _s - LOI	***	6.35

As published models appear to predict lower P release rates than observed, an empirical model for P release was developed from field data. Total P content of the North Basin hypolimnion data was used to develop a relationship between total P and time, or a release rate formula. The hypolimnion data was used to evaluate internal P loading rates. Data for the 2003 and 2004 summer seasons produce similar results. The release rate for 2003 was determined to be $14.5 * T + P_i$ where T is time in days from the onset of stratification and P_i is the initial total P (Kg) in the hypolimnion. The release rate for 2004 was slightly higher at $17.5 * T + P_i$. This is expected as the total P in 2004 was great than in 2003. Rates appear to be linear with time with R² values of 0.84 and 0.98 for 2003 and 2004, respectively.

Summary

The objectives of this study were to investigate the relationship between sediment chemistry and the release, or internal loading, of P into the water column during summer thermal stratification. To achieve these objectives, various field sampling and laboratory test were conducted to elucidate factors influencing the release rate of P during anoxic periods in the hypolimnion. The key tests to be completed were periodic sampling of the water column and sediment, laboratory microcosm studies to simulate anoxic conditions in the lab, and P speciation studies of sediment cores. As new information was gathered during the course of the first year of field sampling, changes in the types and quantities of samples collected were altered to better answer questions of P cycling within Irondequoit Bay.

Examination of water column and sediment chemistry revealed several unique characteristics of P cycling within the Irondequoit Bay system that relate to internal loading during periods of hypolimnetic anoxia. These finding may be summarized as follows.

- The ongoing oxygenation program maintains low dissolved oxygen levels within the hypolimnion during summer thermal stratification.
- Concentrations of P within the water column appear to correlate with the dissolution of Mn oxyhydroxides.
- As a result of oxygenation, Fe oxyhydroxides and their associated P remain within the sediment during summer thermal stratification. This pool of P is not involved in annual cycling, and does not contribute to internal loading at present.
- Core incubation studies correlate well with published models on P release rates.

- Published models predict lower P release rates than observed from field monitoring. This may be the result of a relatively high relative concentrations of P associated with Fe and Mn oxyhydroxides.
- Release rates appear to be linear with respect to time. Variations from year to year are expected based on the initial P concentration of a newly formed hypolimnion, the rate of oxygen depletion and onset of anoxic or low oxygen conditions, and the rate of oxygen supplementation.

Bibliography

Andersen, J.M. 1975. Influence of pH on release of phosphorus from lake sediments. *Archiv für Hydrobiologie* 76: 411-419.

APHA. 1999. Standard Methods for the Examination of Waste and Wastewater. American Public Health Association, 17th ed. New York, N.Y.

Baldwin, D.S., A.M. Mitchell, and J.M. Olley. 2002. 12. Pollutant-Sediment Interactions: Sorption, Reactivity and Transport of Phosphorus. Pages 265-276 in P.M. Haygarth and S.C. Jarvis, editors. *Agriculture, Hydrology, and Water Quality*. CABI pub. Wallingford, UK.

Bannister, T.T., R.C. Bubeck. 1978. Limnology of Irondequoit Bay, Monroe County, New York. In J.A. Bloomfield (ed). *Lakes of New York State-Volume 2*. Academic Press, New York, New York.

Bannister, T.T., A.D. Weidemann, S. Wilke-Mounts and L. Phillips. 1982. Irondequoit Bay Report No. 11: New benthic map of the bay and revised area depth and volume-depth functions. University of Rochester.

Boström, B., M. Jansson, C. Forsberg. 1982. Phosphorus release from lake sediments. *Archiv für Hydrobiologie Beiheft Ergebnisse Limnologie* 18: 5-59.

Boström, B., J.M. Andersen, S. Fleischer, M. Jansson. 1988. Exchange of phosphorus across the sediment-water interface. *Hydrobiologia* 170: 229-244

Drake, J.C., S.I. Heaney. 1987. Occurrence of phosphorus and its potential remobilization in the littoral sediments of a productive English lake. *Freshwater Biology* 17: 513-523.

Eby, G. N. 2004. Principles of Environmental Geochemistry. Brooks/Cole-Thomson Learning, Inc. Pacific Grove, CA

Environmental Health Lab. 2001. Irondequoit Bay Oxygen Supplementation and Monitoring. Monroe County Environmental Health Laboratory, Monroe Co., N.Y.

Goldberg, S., G. Sposito. 1985. On mechanism of specific phosphate adsorption by hydroxylated mineral surfaces: a review. *Communications in Soil Science and Plant Analysis* 16: 801-821

Herbes, S.E., H.E. Allen, K.H. Mancy. 1975. Enzymatic characterization of soluble organic phosphorus in lake water. *Science* 187: 432-434

Holtan, H., L. Kamp-Nielsen, and A.O. Stuanes. 1988. Phosphorus in soil, water and sediment: an overview. *Hydrobiologia* 170: 19-34

- Koshmanesh, A., B.T. Hart, A. Duncan, R. Beckett. 2002. Luxury uptake of phosphorus by sediment bacteria. *Water Res.* 36: 774-778
- Larsen, D.P., J. Van Sickle, K.W. Malueg, P.D. Smith. 1979. The effects of wastewater phosphorus removal on Shagawa Lake, Minnesota: phosphorus supplies, lake phosphorus and chlorophyll-*a*. *Water Res.* 13: 1259-1272
- Larsen, D.P., D.W. Schults, K.W. Malueg. 1981. Summer internal phosphorus supplies in Shagawa Lake, Minnesota. *Limnol. Oceanogr.* 26(4): 740-753
- McRoy, C.P., R.J. Barsdate, N. Nebert. 1972. Phosphorus cycling in an eelgrass (*Zostera marina* L.) ecosystem *Limnol. Oceanogr.* 17: 58-67
- Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. I. *J. Ecol.* 29, 280-329
- Nürnberg, G.K. 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. *Limnol. Oceanogr.* 29(1): 111-124
- Nürnberg, G.K. 1987. A comparison of internal phosphorus loads in lakes with anoxic hypolimnia: Laboratory incubation versus in situ hypolimnetic phosphorus accumulation. *Limnol. Oceanogr.* 32(5): 1160-1164
- Nurnberg, G. 1988. Prediction of Phosphorus Release Rates from Total and Reductant-Soluble Phosphorus in Anoxic Lake Sediments. *Can. J. Fish. Aquat. Sci.* 45: 453-462
- Ostrofsky, M.L., D.A. Osborne, T.J. Zebulsk. 1989. Relationship between anaerobic sediment phosphorus release and sedimentary phosphorus species. *Can. J. Fish. Aquat. Sci.*, 46: 416-419
- Pettersson, K. 1998. Mechanisms for internal loading of phosphorus in lakes. *Hydrobiologia* 373/374: 21-25
- Ruttenberg, K. 1992. Development of a sequential extraction method for different forms of phosphorus in marine sediments. *Limnology and Oceanography* 37: 1460-1482.
- Rydin, Emil. 2000. Potentially mobile phosphorus in Lake Erken sediment. *Water Res.* vol. 34 No. 7 pp 2037 –2042
- Ryding, S.O. 1981. Reversibility of man-induced eutrophication. Experiences of a lake recovery study in Sweden. *Int. Rev. Gesamten. Hydrobiol.* 66:449-502.
- Stumm, W., J.J. Morgan. 1996. *Aquatic Chemistry*, 3rd edn. John Wiley & Sons, New York.

Welch, E. B. 1977. Nutrient diversion: resulting lake trophic state and phosphorus dynamics. U.S. EPA Ecol. Res. Ser. Rep. 600/3-77-003. Corvallis, Oregon.

Welch, E.B. and G.D. Cooke. 1999. Effectiveness and longevity of phosphorus inactivation with alum. *Lake and Reserv. Manage.* 15(1): 5-27

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems 3rd Edition. Academic Press San Diego, Ca.

Yao, W., F.J. Millero. 1996. Adsorption of phosphate on manganese dioxide in seawater. *Environmental Science and Technology* 30: 536-541.