Characterization of Groundwater Phosphorus in Torch Lake

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by
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Introduction

The interchange between groundwater and surface water is both complex and hard to estimate. In general water can come into a lake from the surrounding aquifer and leave the lake in a similar fashion following subsurface hydraulic gradients. Because these flows occur underground or underwater and are relatively slowly varying compared to other sources and sinks, they are difficult to accurately characterize. There are several general principals that will help guide the methods described here. First, groundwater flows are most likely to occur near shore and decrease significantly toward the lake center. This is particularly true in the region around Torch Lake where the subsurface strata is composed mainly of sand and gravel isolated vertically by various layers of clay and not strongly influenced by bedrock barriers. Nevertheless, groundwater is expected to vary significantly though the year and be localized by subsurface irregularities and topography. No one has tried to measure these phenomena in the Elk Rapids Chain of Lakes watershed and no monitoring systems are currently in place to observe the flows.

The groundwater piezometers are installed following the plan developed for a similar study on Lake Whatcom, WA[1] and a plan specific to Torch Lake. [2,3] Further, we were guided by several previous surveys on Torch Lake. First, a survey of cladophora around the lake edge has recently been carried out.[4] Cladophora is used as a monitor for phosphorus discharges from septic, fertilizer, and natural sources. These areas of the lake are likely to be those most responsible for bringing phosphorus into the lake. Several wells will be place both in cladophora free and cladophora ridden areas for comparison. Second, a survey has been carried out of well logs for residences around Torch.[5] These well logs have been required of well drillers by the county since 1970 and since the rate of development around the lake has been rapid during this timeframe, well logs for over half of the lakeshore residences have been recorded. For our purposes these logs show the subsurface strata down to the level of the wells and in a few cases show the bedrock level. These records give the depth of sand, gravel, clay, and shale layers until well water is found typically at 80 ft. or so. That is, the shallow subsurface strata around the lake are relatively well known and are composed mainly of sand and gravel, with some clay layers. Typical well logs on the north, east, and west sides of the lake have 10-30 ft. of sand and gravel, 10-30 ft. of clay, and 10-30 ft. of sand below that, the wells being drawn from the lower layer of sand. At the southern end of the lake the clay layer is within a few feet of the surface and can be 10-100 ft. thick with sand below. Thirdly, lake bottom near the lakeshore of Torch is composed primarily of sand and gravel and, except near significant points of land extending into the lake, the lake bottom falls gently from the shore to a depth of about 12 feet after which there is drop-off either to a secondary shelf at 40-45 feet or to the lake bottom at 200-300 feet. The south end has sand beaches with extensive sandbars extending 1,000 feet into the lake. There are no swampy, sediment rich, or plant covered areas around the lake edges. In this respect the material through which groundwater flows is relatively homogeneous. Fourthly, we have some anecdotal information about springs and seeps around the lake. Typically, swimmers have noticed regions of the sandbar that are colder than the surrounding water. These are probably groundwater seeps but the regions are neither constant nor stationary. Divers have also noticed that swimming along the drop-off, the water closest to the shelf is coldest. These observations indicate seeps of a more constant nature. Finally, most lake residents have heard stories of boiling springs at the bottom of Torch seen by divers. There is no documentation of these phenomena and there are no photographs. One would expect that a significant spring would have low dissolved oxygen associated with it and could be observed from low DO readings in lake profiles. None have been seen, but no systematic surveys have been done. Divers may be fooled by sediment slumps on the steeper edges of the lake.

Land use around Torch Lake is shown the Fig. 1 and the Torch Lake watershed is shown in Fig. 2. Of the 1700 lakeshore parcels more than 85% developed and consist mainly of single family dwellings. Of these dwellings approximately 90% are occupied only during the summer months, June – Aug. The population of “second tier” residences, that is residences that fall in the layer of properties just outside those on the lakeshore, around the lake is small (~20%) but growing. Most of the land outside of the riparian residences is farm or forest land. In the Torch Lake watershed region forested and agricultural land are about equally divided. In addition many of the farms are not heavily worked and some are fallow. Cluster developments in the Torch watershed are still rare. Finally, there are no cities or industries on the lake. The largest village, Alden, has approximately 1,000 residents and the four other unincorporated villages, Clam River, Torch River, Eastport, and Torch Lake Village, are considerably smaller. None have central sewage systems nor central water. All residences have individual septic systems for waste disposal. The Chain of Lakes above Torch has three towns Ellsworth, Central Lake, and Bellaire, with populations of 500, 1,200 and 1,000 respectively and no major industries. Bellaire and Central Lake have central sewage systems (as does Elk Rapids, pop. 1,700, where the Chain empties into East Grand Traverse Bay). The total population of all the townships touching Torch Lake is approximately 7,000. And the population of Antrim County in which most of the Chain of Lakes watershed resides in about 23,000. All population and most land use figures are for the year 2000.

Several test wells have been driven to acquire information to help guide our choice of depth and location for the monitoring network. Four wells have been driven in a sand beach near the shoreline at the north end of Torch the winter before the network was installed. Table 1 below shows several typical parameters for wells and different depths and shoreline locations taken in early April, 2005 just after the ice had gone out. Each of these wells was pumped for a few hours until the water became clear. The hydraulic head of each was measured and each was tested with the Hydrolab Quanta for temperature, dissolved oxygen (DO), pH, and specific conductivity. For wells less than five feet deep, the hydraulic head has been almost unobservable and the water sampled from these wells has been more like the lake water than groundwater. At about five feet and below the water is characterized by a low DO content and high but variable specific conductivity (because it has more minerals dissolved in it). The existence of a hydraulic head appears to be correlated with a lowering in DO. The well driven 7.0 ft. into the bottom in 3.5 ft. of water 145 ft from the lakeshore is similar to the 11 ft. well at the shoreline except that the hydraulic head varies considerably from week to week. Water drawn from a 50 ft. deep nearby cottage well has the lowest DO at 4.4 mg/l.

Depth (ft.)	Location	Head (in)	Temp. (C)	DO (mg/l)	pH	Sp. Cond. (ms/cm)
0	shore	---	2.0	12.5	8.4	0.30
2	shore	0.0	1.6	12.2	8.2	0.41
5	shore	0.0	5.0	8.02	7.4	0.94
11	shore	1.0	10.6	8.4	7.5	0.38
7	145 ft into lake	1.0-5.0*	10.6	8.6	7.5	0.45
50**	cottage well	----	10.9	4.4	7.5	0.58

* Varies from day to day.

** This is a sample from a domestic well near the same location.

Table 1: Data from the Hydrolab Quanta instrument and hydraulic head measurements are shown for several well depths near the Torch lakeshore

Monitoring Network

Permission has been obtained from about twenty Three Lakes Association members who are Torch Lake riparians to sink a shallow groundwater well a few feet off shore. The distribution of wells is determined by dividing the lake into sectors and finding volunteer in each sector. Written permission has been obtained to set the wells and sample from them during the spring, summer, and fall of 2005. These wells will be set by pounding down a 3/8" ID, 5/8" OD steel well pipe which will carry a point and screen attached to _" OD translucent polyethylene tubing. The steel pipe is withdrawn leaving the point and screen at the bottom connected to the surface by the plastic tube. This tube marks the location of the well and the place from which samples will be drawn and measurements made. The GPS (Global Positioning Satellite) and physical location are noted and marked with brightly colored surveyor tape.

Of the 21 sites identified only 13 piezometers locations were used. This is because the remaining sites were found to have a significant layer of clay at or just beneath the water level. After failing to successfully establish several wells because of clay, it was found that a simple _" steel rod could be used to probe the porosity of the sand and gravel. When the rod could be pushed over a foot into the bottom, piezometer wells were found to work, that is, water could be pumped from them and a head level could be measured.

Figure 1 shows the Elk River Chain of Lakes land use,[6] and Figure 2 shows the extent of the watershed of Torch Lake. [7] The total area of the watershed, excluding that associated with Clam River and the upper chain of lakes is about 1.6 times the lake area. Maps in Figures 3 - 6 show the location of the piezmeters that will be used in this survey.

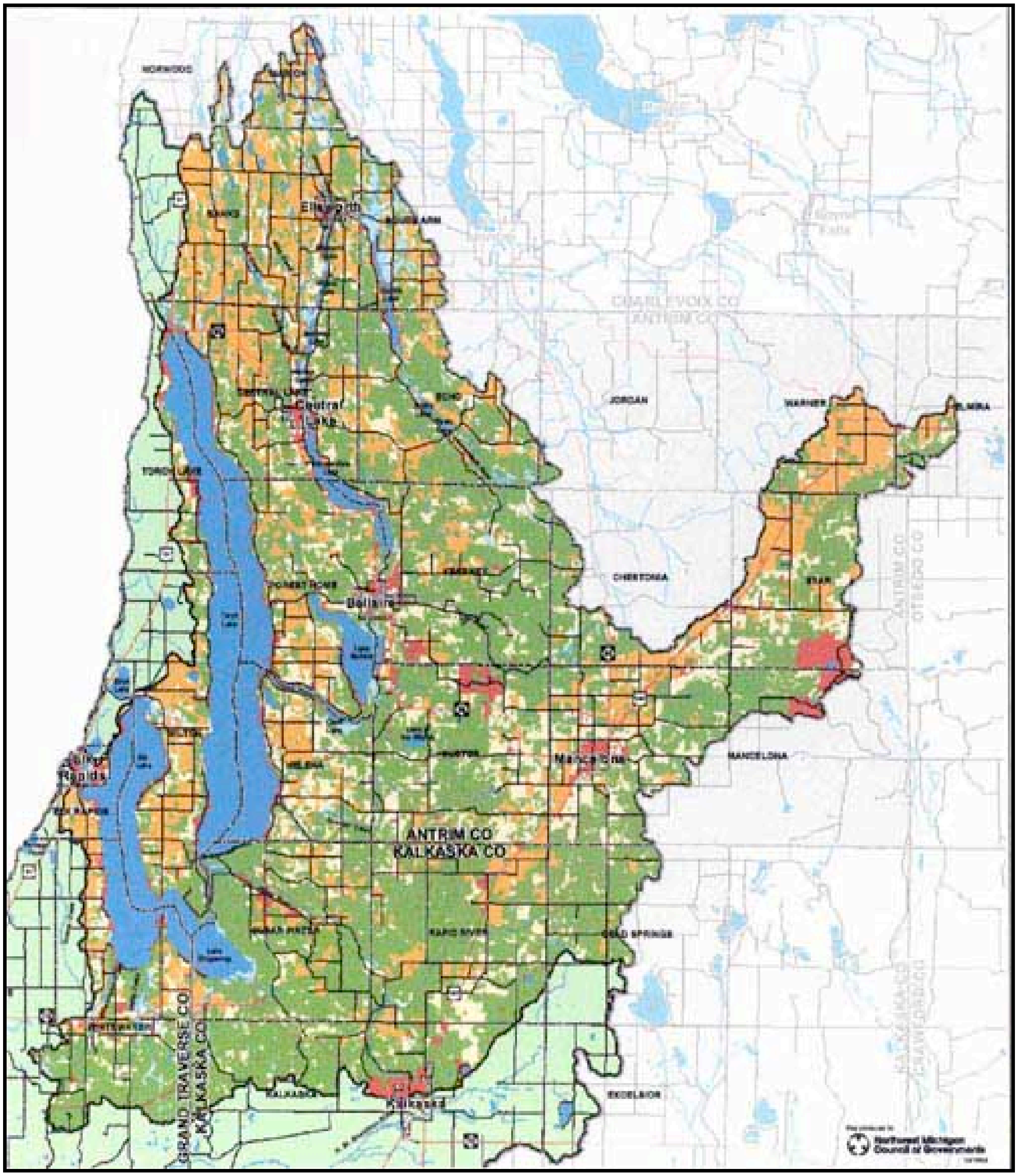


Fig. 1 – Land Use map of the Elk River Chain of Lakes Watershed.

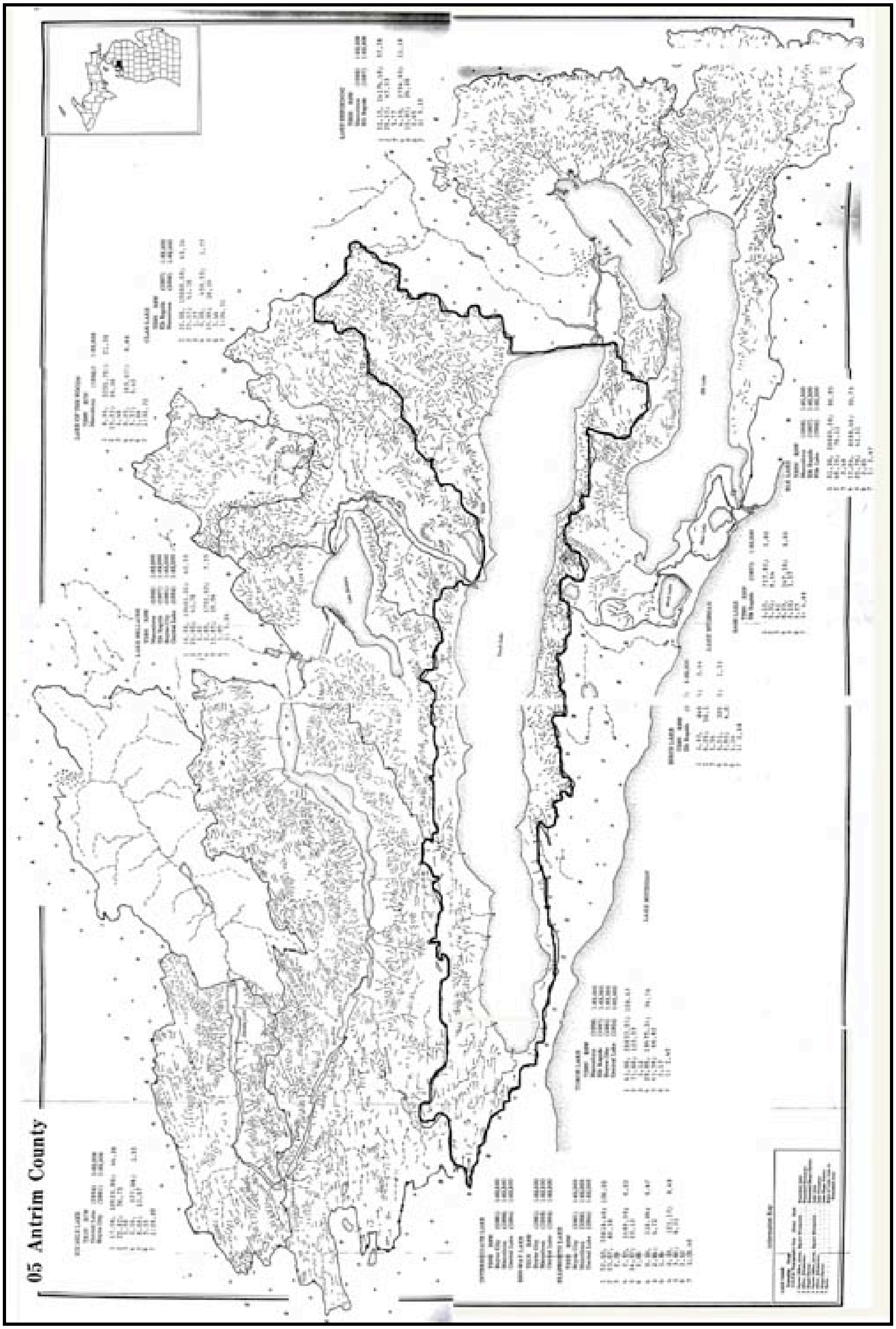


Fig. 2 Torch Lake watershed region.

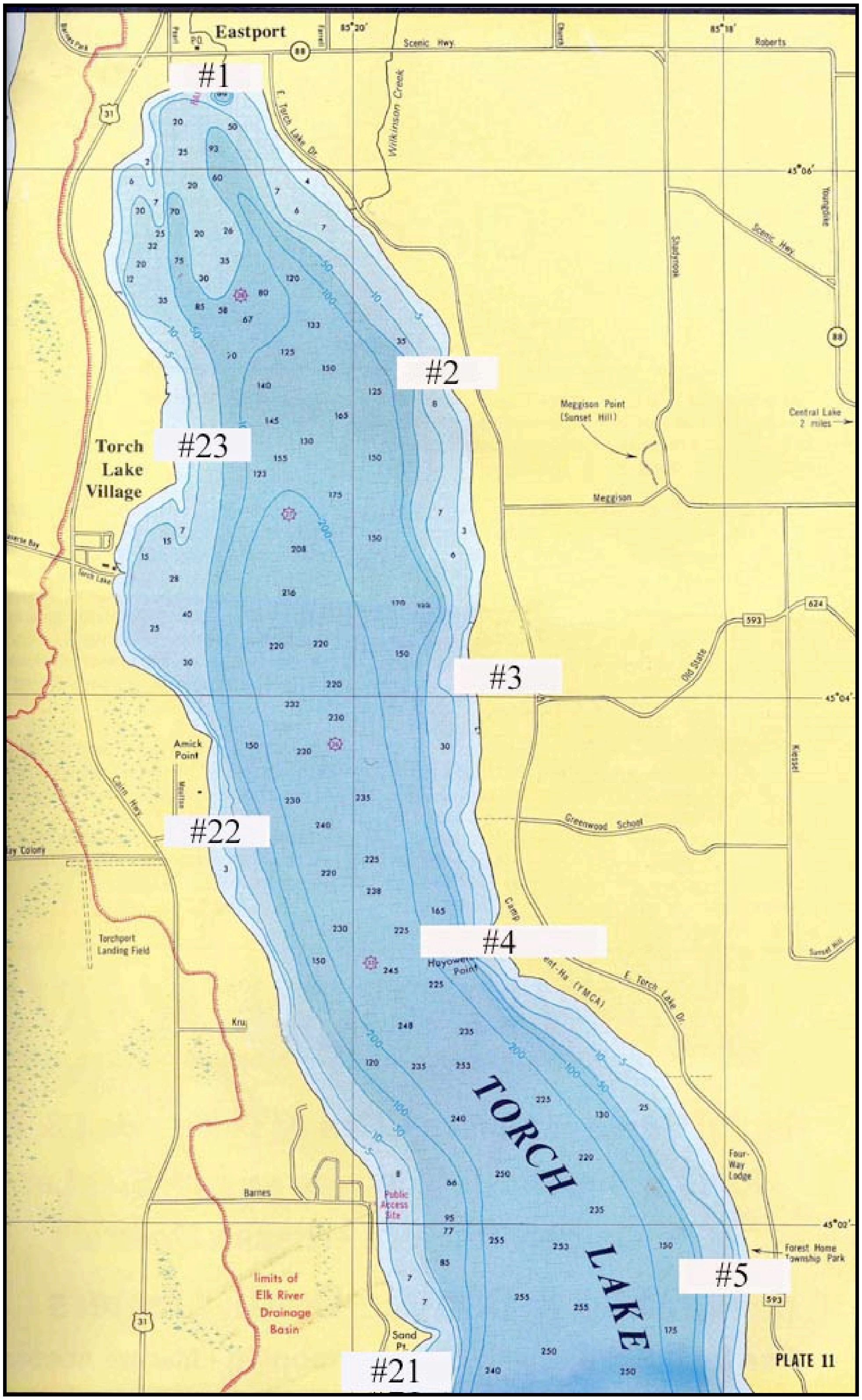


Fig. 3 - Northern third of Torch Lake

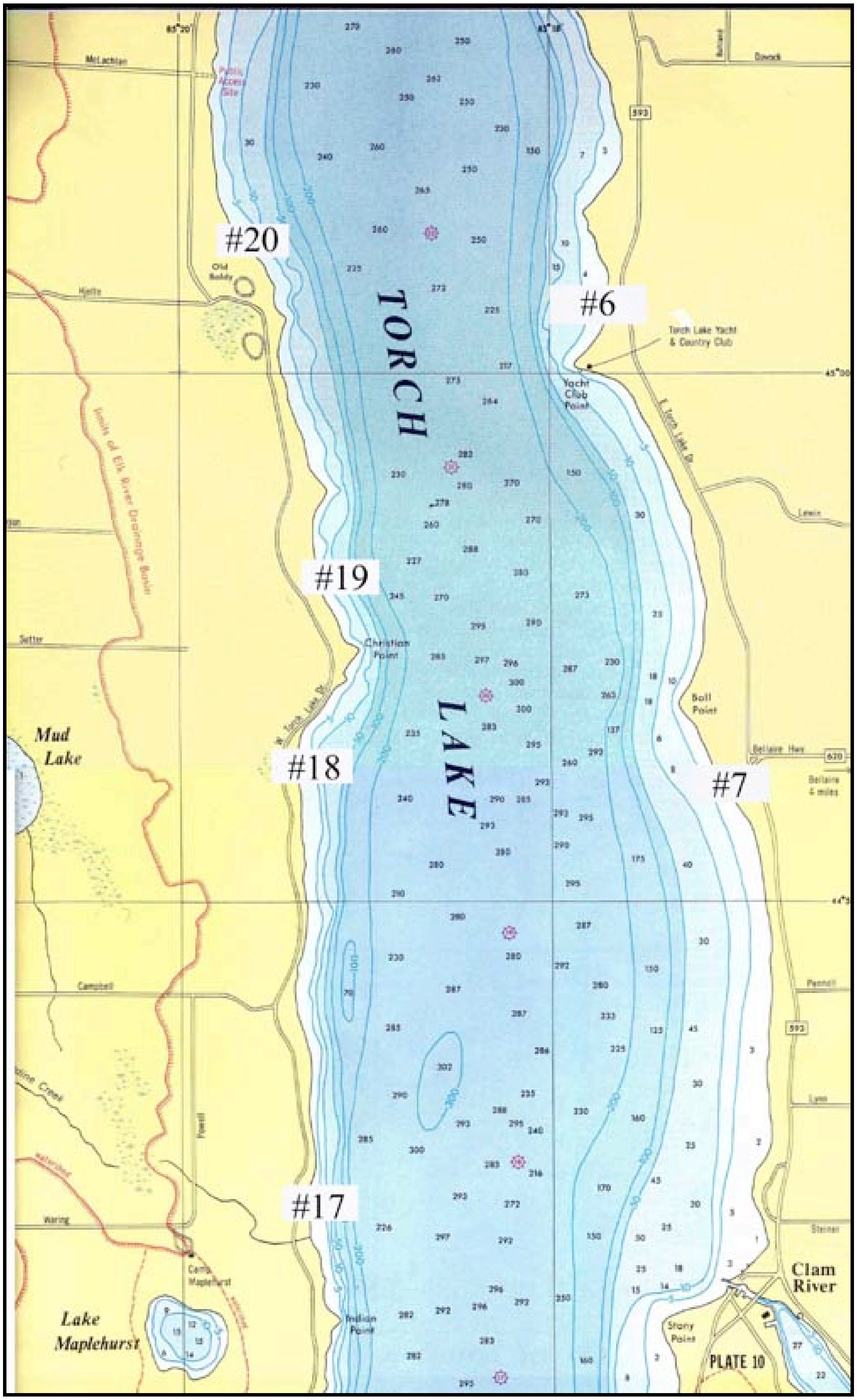


Fig. 4 - Middle third of Torch Lake

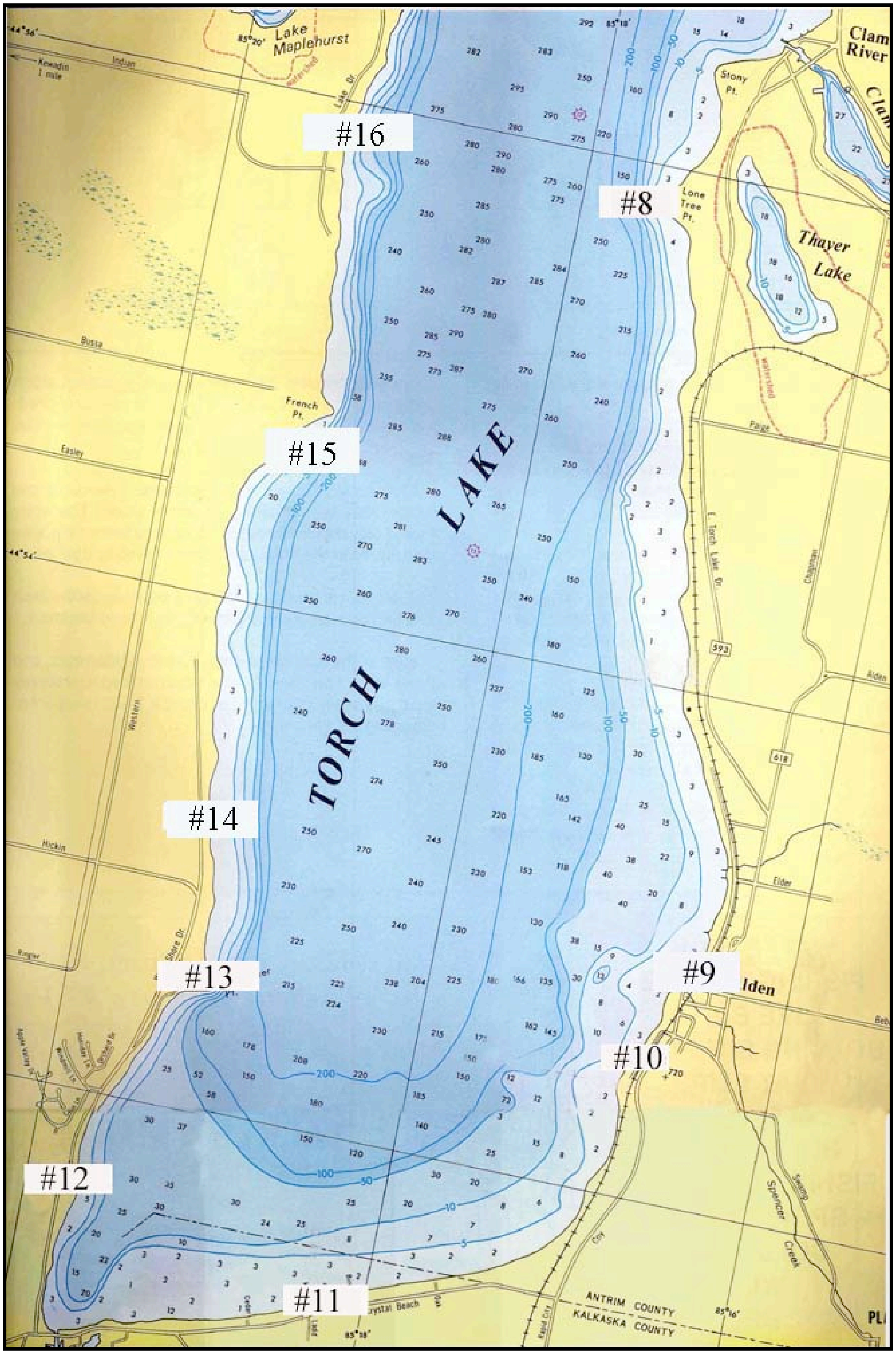


Fig. 5 - Southern third of Torch Lake

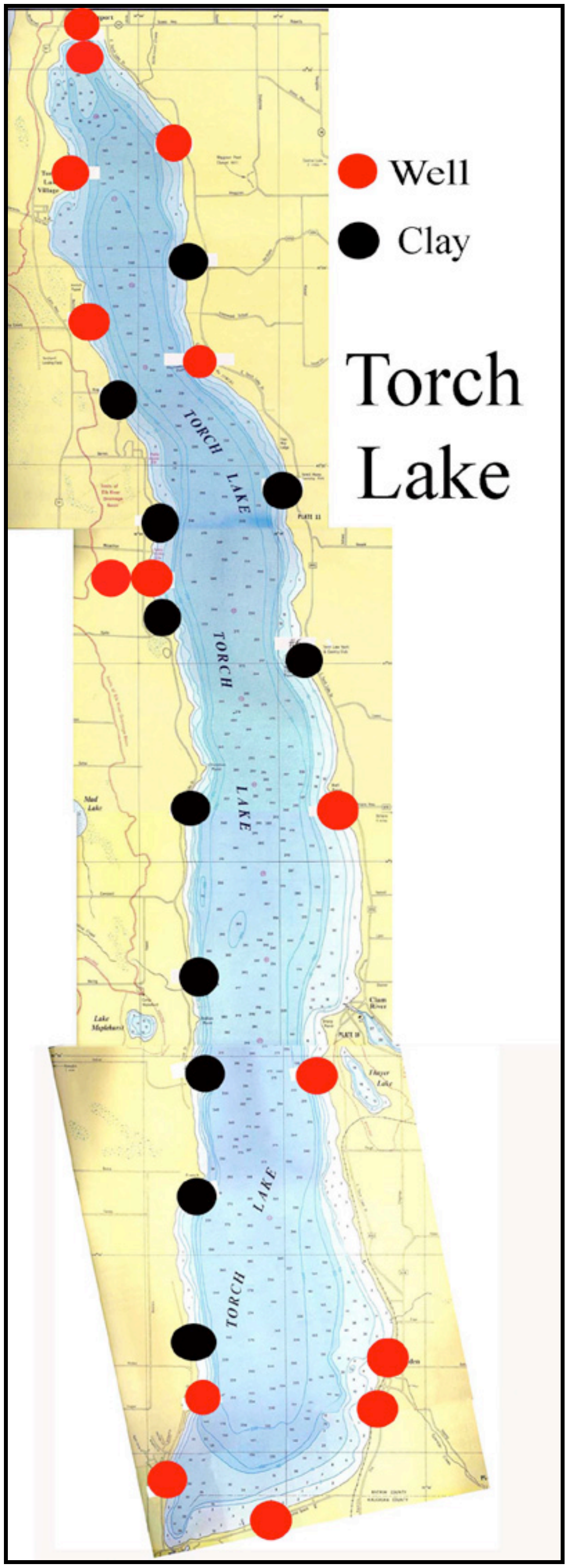


Fig. 6 – Synopsis of Torch Lake piezomter sites

Groundwater Phosphorus and Hydraulic Flow Sampling Plan

Phosphorus samples will be taken as described in Table 2 from May through Sept. of 2005. There were 13 separate locations but two locations had two wells each.

	May	June	July	Aug.	Sept.
Number of TP locations	15	0	15	0	15
Number of paired lake samples	5	0	5	0	5
Number of phosphorus analyses	20	0	20	0	20
Number of Flow measurements	15	0	15	0	15

Table 2. Phosphorus and hydraulic flow sampling schedule

Before each well was set samples of distilled water were drawn through the same apparatus to establish a baseline of possible contamination from the materials in the point, screen, and tubing. These blank samples were processed in the same way as actual well samples.

The cost of a typical phosphorus analysis is about $20 and our budget will not allow an indefinite number of samples. The numbers given here represent a judgment about how to distribute our sampling budget among the lake, the tributaries, the sediment, and the groundwater. The total number of samples in this series is 60.

Samples will be drawn from the wells with an electric pump following the protocol given below. Phosphorus sample bottles will be supplied by GLEC and analyzed according to GLEC Standard Operating Procedures.[8]

In addition to the phosphorus analysis sample will be drawn and a record of temperature, pH, dissolved oxygen, and specific conductivity will be taken with the TLA Hydrolab Quanta.[9] The Hydrolab Quanta will be calibrated each day according to the Hydrolab and GLEC protocols.[10] The hydraulic measurement protocol is described below.

The piezometer were installed with a "hammering" derrick as shown in the photograph in Fig. 6. The 1/2" steel pipe will be driven into the ground by repeatedly hammering the top of the pipe with a heavy weight. The weight is guided over the smaller well pipe by a pipe of larger diameter so that the hammer will fall directly on top. The _ " OD plastic tubing (ID = 0.12") will come up through the center of this weight as it slides up and down. The derrick has a pulley at the top with which to raise and lower the hammer weight and a come-along to remove the pipe once the point has been driven to the desired depth. This apparatus has been tested on a number of test wells and if used with care should allow the same pipe to be used over and over leaving only the points, screen, and tubing behind.

The point is made of steel and has a shoulder that fits loosely in the bottom end of the well pipe. The screen is made of polyester mesh with a pore diameter of about 0.1-0.3 mm, otherwise known as no-see-um mosquito netting. The plastic tubing is perforated and anchored to the point. About 3” of mesh is wrapped three times around the tubing and secured with stainless steel wire (Fig. 7) resulting in an effective pore size of about 0.1 mm. The polyester mesh with some typical beach sand is shown in Fig. 8. The point assembly is thoroughly rinsed in alcohol and distilled water and wrapped in a plastic bag before being deployed.

Fig. 6 Hammering derrick being used to set a well on Torch Lake

Fig. 7 - Well point, mesh screen, and sampling tube

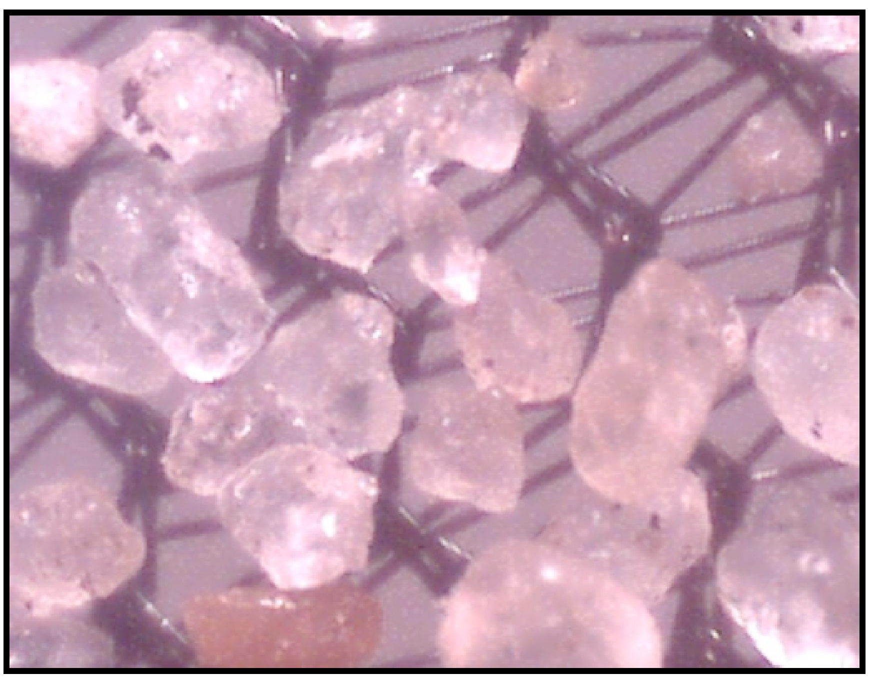


Fig. 8 - No-see-um polyester mesh with typical beach sand.
The largest holes will pass a grain with a diameter of 0.3 mm.

Hydraulic Sampling Methodology

The methodology for measuring hydrological flows follows methods described by Hvorslev,[11] Cherry and Lee, [12] and summarized in Lambe and Whitman. [13] The piezometers will also be used as simple sampling probes to determine the phosphorus content of the flowing water. In addition we have developed a criteria for choosing the appropriate depth for the piezometers based on a survey of water well records and on insitu measurements of the sample water. We will be using a particularly simple case for measuring the vertical flow of groundwater into the lake bed using a single piezometer inserted into the ground a sufficiently small distance into the aquifer that the flow field has no horizontal components. In this case one can obtain a simple estimate of both the hydraulic vertical gradient, dh/dl, and the hydraulic conductivity, K_h. Then using Darcy's equation one can estimate the total flow rate if one can estimate the area over which this flow takes place. The assumptions, measurements, and calculations are discussed below.

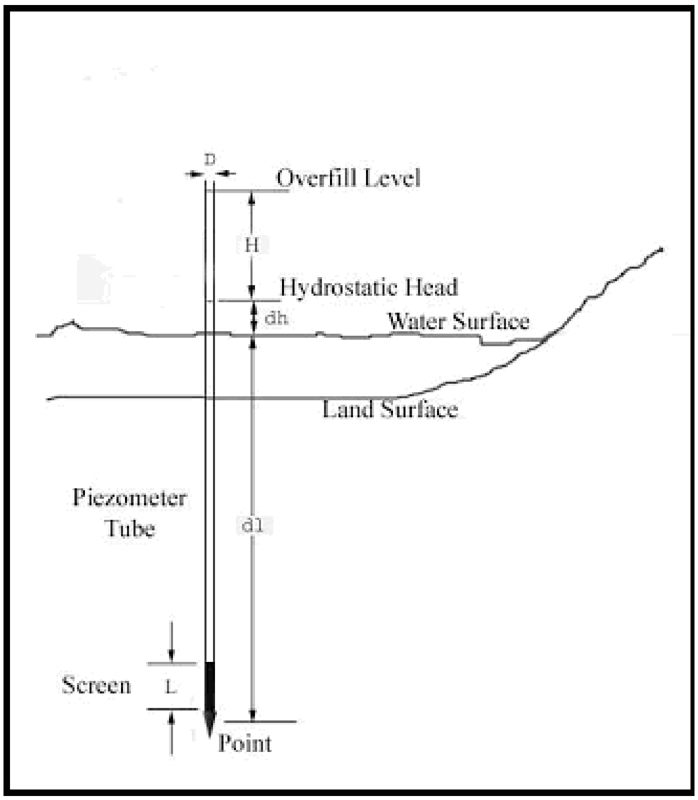


Fig. 9 – Variables used in piezometer calculation

Fig. 9 shows an idealized picture of the piezometer and the variables that need to be measured. We assume that the groundwater flow is vertical, into the lake and therefore the hydraulic head, dh, is positive, that is, the water in the piezometer tube will rise above the water surface. This is commonly known as an artesian system. The gradient length, dl, is the depth of the piezometer sampling region below the water surface, so that dh/dl is a unitless number. We further assume that the hydraulic conductivity is isotropic, that is the horizontal and vertical components are the same ($K_v = K_h$) as would be expected in a uniform medium. As long as the tube is transparent, the hydraulic head can be measured with a ruler. The well depth, dl, must be measured in the same units. Darcy's equation relates the flow to the hydraulic gradient, dh/dl, and the hydraulic conductivity as follows:

$$Q = A(dh/dl)K_v.$$

where Q is the groundwater flux or flow rate (cubic feet per second)
A is the area over which the flow takes place (square feet)
dh/dl is unitless
K_v is the vertical hydraulic conductivity (feet/second)

The groundwater flux can be determined if one can estimate A and measure $K = K_v$. To measure K one fills the piezometer with water to a height, H. If nothing further is done, the water level will return to its equilibrium level, dh. The lower the groundwater conductivity, the slower the return to equilibrium.

The groundwater hydraulic conductivity, K, is determined by the falling head method. The piezometer tube is filled to a height H_2 and allowed to fall to H_1 in time t_2-t_1. The following formula then gives the conductivity

$$K = [D^2/8L(t_2-t_1)]\ln\{(L/D) + [1+(L/D)^2)]^{1/2}\}\ln(H_2/H_1)$$

If L/D > 4

$$K = [D^2/8L(t_2-t_1)]\ln[2(L/D)]\ln(H_2/H_1)$$

D is the inside diameter of the piezometer tube (inches)
L is the length of the well screen (inches)
ln is the natural logarithm, $\ln = 2.3\log_{10}$.

Our piezometers are all the same and have D = 0.17" and L =3.0", however, because of varying soil conditions the depths, dl, are not identical but fall in the range 3-10 ft..

In practice the piezometers must be placed in a region in which groundwater infiltration is occurring, the points must not be clogged with clay or sediment, and for our purposes of measuring the phosphorus groundwater flux, should be placed at a level which samples the shallow groundwater of recent origin. That is we would like to be sampling water that has been flowing beneath residences for the last year or so. This last part requires some judgment and experience, but we will summarize what has been learned in the Torch Lake watershed from several test wells.

The procedure has been as follows:

(1) Before driving the piezometer a blank total phosphorus (TP) sample is first drawn from the test point immersed in distilled water. The test well/peizometer is then

driven and steel driving pipe withdrawn leaving the well point connected to the surface with the _" OD polyethylene tubing.

(2) The well number, residence, date, depth, and location of the well/piezometer will be recorded with a GPS and distance measurements to nearby landmarks (see the attached well/piezometer field test sheet).

(3) The test well/piezometer is pumped with a 12v. vane bilge pump for a period of 15 minutes or until the water runs clear. If the well conduction is low, the well may be "developed" by pumping surface water into the point until a several liters can be drawn from the well in less than 10 minutes. On a number of occasions the wells were found to be unusable because there was no conduction. If a suitable nearby location could not be found, the site was abandoned. The same pump is used for all types of sampling on all wells.

(4) The well/piezometer is then plugged, buried, marked with brightly colored surveyors tape, and left for a week in order to allow the normal ground water flows to come to equilibrium.

(5) After a period of a week the piezometer location is revisited and total phosphorus (TP) sampled, the hydraulic head measured, and the hydraulic conductivity determined by the falling head estimate. We have taken $H_2 - H_1 \sim$ 24-36" which generally gives a fall time of 1-10 sec. Typically, a liter of water is drawn before the sampling takes place.

(6) The piezometer water is tested with a Hydrolab Quanta[14] to measure the temperature, dissolved oxygen (DO), specific conductivity, and pH. A similar sample of nearby lake water is measured at the same time and recorded.

(7) Three sets of measurements were carried out on all wells between May and Sept. of 2005. One set of wells at a single site was in place from Feb. – Dec. 2005 to study the extent of the flows perpendicular to the shoreline and to do preliminary studies prior to establishing the full array.

(8) At the end of the summer of 2005 all but four wells were plugged and abandoned injecting a bentonite-based grout slurry through the _ inch tubing. Four wells were left in place on the north and south ends and center east and west shores to be used to examine seasonal patterns.

Data, Analysis, and Discussion

Tables 3-7 summarize the data which was collected and the analysis of the water and phosphorus flow following the formulae found above. The columns are as follows:

Well #	As shown on the Torch Lake map
Perimeter Distance	Starting with piezometer #1
Perpendicular Distance	Piezometer distance from shore.
Date	Date of measurement
Lake TP	Total Phosphorus in ppb from lake sample
Piez TP	Total Phosphorus in ppb from piezometer
dl, dh	Head height, piezometer depth in inches.
T2-T1	Time to fall H2-H1 in seconds

H2, H1	Fall distances H2>H1 in inches.
$Kx10^6$	(Conductivity)x(10^6) in ft/sec
S	Shoreline distance for a given piezometer in feet
$Ax10^{-6}$	Total area = (Shoreline distance) x Yx 10^{-6}
Y	Effective distance into the lake over which ground water flow occurs.
Q	Calculated water flow rate (cfs)
TPQ	Phosphorus flow rate (kg/yr)

The numbers shown in red are estimates based on the average of other data in the same piezometer set. We have taken as constants L=3.0", D=0.12", Y=100', and the shoreline distance is estimated to be half the distance to adjacent wells in either direction with one exception. Well #19 is unusual. The well point could be pushed down almost 10' by hand as if groundwater were raising the sand continuously. This rapid flow region was sandwiched between regions with clay which represented no flow at all in our model. We found that the high flow region only extended a few lots on either side of the piezometer and have taken its effective shoreline distance to be 400 ft. Subsequent sampling of the west shore revealed a few other high flow regions of similarly limited extent. Flow from these narrow regions has been ignored in our final estimates. An examination of the contribution of Well #19 show that it contributes less than 0.1% of the total.

Two locations had several piezometers. Station #1 had three and station #19 two. Station #1 was used to examine the extent over which the groundwater flow extended into the lake. Station #19 was used to examine the difference with depth. These two piezometers were set at 6 and 9 ft. Earlier data on the change in hydraulic activity with well depth on Well #1 was shown in Table 1.

The flow values have been calculated for each measurement on each piezometer site and averaged. Figures 10 and 11 show the average flow at each site. The average of all Torch Lake reference and piezometer total phosporus, TP, measurements is 2.0 and 21.7 ppb, respectively. The lake samples are typical of the volume average for the entire lake at 2.6 ppb and the piezometer samples are typically more than ten times higher. The variation in measurements at a particular site is significantly less than the variation between sites for both water and phosphorus flows. 52% of the total water flow comes from two of the sites, #1 and #9, while these same two sites produce 36% of the total phosphorus flow. Only one piezometer per site is used for the average and total flows, and of course, the sites marked "clay" do not contribute at all.

The uncertainty in these measurements is undoubtedly quite large. First, the subsoils are not very uniform in composition. This is evident from the residential well records and from experience on the sites. Sometimes it was necessary to probe several locations before a site could be found which was porous enough to even try a well. Some wells appeared to flow at first, but stopped after being plugged by silt and could not be recovered. The clay regions clearly had occasional gaps like site #9 which flowed strongly but only over a limited shoreline distance. Even on the east side of the lake which was generally free of clay, there were three sites which had clay deposits. And of the sites which showed flow there was considerable variation. However, even more importantly our estimate of the distance into the lake over which these piezometer wells have been assumed to flow is relatively arbitrary. We have taken 100 ft. and have data from site #1 for undiminished flows as far as 400 ft. into the lake. A better knowledge of the subsurface permeability is needed to understand these factors. As a practical matter, we will assume that the total water flow can be estimated independently from the difference between all the other inflows and outflows in Torch Lake and an upper limit on the flow can be found from the rainfall on the Torch Lake watershed. For the 2005 season the difference estimate is in the range 30-60 cfs and the watershed upper limit based on the yearly average rainfall (and no evaporation) is about 100 cfs. So the 100 ft. estimate perpendicular to the shore is in the right range. As importantly, the variation in the ground water and phosphorus flows shown in figures 10 and 11 make sense only if the 100 ft. estimate is a constant around the entire perimeter of the lake and this is also probably not very precise. Finally, we have made all these measurements during the summer months, and we do not know what happens the rest of the year.

What is the correlation between the groundwater phosphorus and other activities around Torch Lake? The general pattern of groundwater phosphorus and the pattern of cladophora blooms do not correlate well as shown in Figure 11. And the site that produced the largest phosphorus flow on the lake corresponds to the single relatively undeveloped region on the lake. It consists of a two mile stretch that is used as a boys camp only in the summer, has no known septic problems, no development for several miles behind the camp, and relatively low land use compared to other regions of the lake.

What fraction of the shallow phosphorus comes from anthropomorphic activities? There as been no attempt in this work to determine what part of the phosphorus that was measured in shallow ground water comes from septic, fertilizers, or natural sources. However there is information from other studies that bears on this issue. One study on Long Lake[15] sampled total phosphorus level in drinking water wells which is expected to be taking water which is untouched by human activity. The Long Lake region is similar in subsoil properties to that of the Torch Lake region. The average TP values associated with these wells was 9.7 ppb with a range in eight samples of 1.5 to 25.0 ppb. Five of the Torch Lake sites had averages below 9.7 ppb and ten were above this level, the highest having an average of 66 ppb. In the single example of a well on Torch Lake, #19, at the same site with two different levels, 6 and 9 ft. the lower one had less TP, 21.7 ppb versus 12.0 ppb, respectively. So it appears likely that a significant fraction of the groundwater phosphorus is from human activity.

A second, more indirect measurement that relates to the issue of what effect human activity has had on the phosphorus levels in Torch Lake is a measurement of the historical phosphorus record of Elk, Bellaire, and Intermediate Lakes done by researchers at the Limnological Research Center at the University of Minnesota in 1993.[16] Ground water will be shown to contribute as much as half of the input to Torch Lake. Thus, the phosphorus level in Torch Lake and the rate at which phosphorus enters from ground water should be correlated. Dated core samples of these lakes were examined and, based on diatom ratios which are sensitive to the lake phosphorus level, the phosphorus level as found to have changed little during the last 300 years. This would imply that the input phosphorus levels have not changed either. Torch Lake was not measured but Elk and Bellaire certainly ought to be similar.

well #	Peri. Dist. (mi)	Perp. Dist. (ft.)	Date	Lake TP (ppb)	Piez TP (ppb)	dl (in)	dh (in)	T2-T1 (s)	H2 (in)	H1 (in)	K*(10**6) (ft/s)	dh/dl	S (ft)	A*(10**-6) (ft^2)	Q (cfs)	TPQ (kg/yr)
1	0	0	5/16/05			36.0	1.0	6.0	36.0	12.0	35.81	0.0278	10,300	1.03	1.02	0.0
		140	4/9/05			89.0	1.0	7.0	36.0	12.0	30.70	0.0112	10,300	1.03	0.36	
			5/2/05	1.7	20.0	89.0	0.3	3.6	36.0	12.0	59.69	0.0034	10,300	1.03	0.21	3.7
			5/16/05			89.0	1.0	6.0	36.0	12.0	35.81	0.0112	10,300	1.03	0.41	
			6/25/05	1.0	12.6	89.0	0.3	6.5	24.0	12.0	20.86	0.0028	10,300	1.03	0.06	0.7
			8/4/05		18.0	89.0	1.5	4.0	24.0	12.0	33.90	0.0169	10,300	1.03	0.59	9.4
			9/29/05		18.6	89.0	2.0	3.0	24.0	12.0	45.19	0.0225	10,300	1.03	1.05	
			10/5/05			89.0	0.2	4.0	36.0	12.0	53.72	0.0022	10,300	1.03	0.12	
			Avg	1.4	17.3							Avg.	10,300	Avg	0.4	4.59
		400	10/5/05			60.0	0.7	10.0	36.0	12.0	21.49	0.0117	10,300	1.03	0.26	
2	1.9	35	5/2/05	4.4	27.5	24.0	1.5	2.0	24.0	12.0	67.79	0.0625	8,700	0.87	3.69	90.1
			6/21/05	3.6	29.2	24.0	1.0	1.0	36.0	12.0	214.89	0.0417	8,700	0.87	7.79	202.1
			8/4/05	4.0	55.0	24.0	1.5	2.0	24.0	12.0	67.79	0.0625	8,700	0.87	3.69	180.2
			9/29/05		30.8	24.0	1.0	2.0	24.0	12.0	67.79	0.0417	8,700	0.87	2.46	67.3
			Avg	4.0	29.2							Avg	8,700	Avg	4.4	135
3	3.3	25	Clay												0.0	0.0
4	4.6	20	7/7/05		30.2	42.0	8.0	1.0	24.0	12.0	135.58	0.1905	8,700	0.87	22.47	602.9
			9/1/05	2.4	30.8	42.0	8.0	1.0	24.0	12.0	135.58	0.1905	8,700	0.87	22.47	614.9
			9/29/05		21.4	42.0	6.0	1.0	24.0	12.0	135.58	0.1429	8,700	0.87	16.85	320.4
			Avg	2.4	27.5							Avg	8,700	Avg	22.5	512.8

Table 3

Spreadsheet showing the phosphorus results and hydrological data and flow estimates for the NE Torch Lake piezometers.

	Peri.	Perp.														
	Dist.	Dist.	Date	Lake TP	Piez TP	dl	dh	T2-T1	H2	H1	K*(10**6)	dh/dl	S	A*(10**-6)	Q	TPQ
well #	(mi)	(ft.)		(ppb)	(ppb)	(in)	(in)	(s)	(in)	(in)	(ft/s)		(ft)	(ft^2)	(cfs)	(kg/yr)
5	6.6	15	Clay												0.0	0.0
6	8.7	40	Clay												0.0	0.0
7	10.9	50	6/21/05	2.2	56.0	24.0	3.5	5.0	36.0	12.0	42.98	0.1458	15,300	1.53	9.59	477.2
			7/28/05		72.1	24.0	7.5	30.0	24.0	12.0	4.52	0.3125	15,300	1.53	2.16	138.4
			9/30/05		70.7	24.0	4.0	6.0	24.0	12.0	22.60	0.1667	15,300	1.53	5.76	362.0
			Avg	2.2	66.3							Avg	15,300	Avg	5.8	325.9
8	14.5	25	6/21/05	1.6	28.3	36.0	0.5	1.0	36.0	12.0	214.89	0.0139	18,700	1.87	5.58	140.4
			7/28/05	3.2	30.9	36.0	3.5	2.0	24.0	12.0	67.79	0.0972	18,700	1.87	12.32	338.4
			9/30/05		25.9	36.0	1.0	2.0	24.0	12.0	67.79	0.0278	18,700	1.87	3.52	81.0
			Avg	2.4	28.4							Avg	18,700	Avg	7.1	186.6
9	18.1	20	8/4/05		3.6	42.0	7.5	1.0	24.0	12.0	135.58	0.1786	10,800	1.08	26.15	83.6
			9/29/05		6.0	42.0	8.0	1.0	24.0	12.0	135.58	0.1905	10,800	1.08	27.89	148.7
			Avg		4.8							Avg	10,800	Avg	27.0	116.2
10	18.6	15	6/21/05	3.3	10.2	24.0	3.0	1.7	40.0	16.0	105.43	0.1250	6,600	0.66	8.70	78.8
			7/28/05		9.2	24.0	3.0	2.0	24.0	12.0	67.79	0.1250	6,600	0.66	5.59	45.7
			10/2/05		4.6	24.0	4.5	2.0	24.0	12.0	67.79	0.1875	6,600	0.66	8.39	34.3
			Avg	3.3	8.0							Avg	6,600	Avg	7.6	52.9

Table 4
Spreadsheet showing the phosphorus results and hydrological data and flow estimates for the SE Torch Lake piezometers.

	Peri. Dist.	Perp. Dist.	Date	Lake TP	Piez TP	dl	dh	T2-T1	H2	H1	K*(10**6)	dh/dl	S	A*(10**-6)	Q	TPQ
well #	(mi)	(ft.)		(ppb)	(ppb)	(in)	(in)	(s)	(in)	(in)	(ft/s)		(ft)	(ft^2)	(cfs)	(kg/yr)
11	20.6	25	6/30/05	1.4	60.5	24.0	1.0	2.0	24.0	12.0	67.79	0.0417	10,600	1.06	2.99	161.0
			7/28/05	3.1	11.5	24.0	1.0	2.0	24.0	12.0	67.79	0.0417	10,600	1.06	2.99	30.6
			9/29/05		10.0	24.0	2.0	2.0	24.0	12.0	67.79	0.0833	10,600	1.06	5.99	53.2
			Avg	2.3	27.3							Avg	10,600	Avg	4.0	81.6
12	22.6	20	6/30/05	1.5	27.5	24.0	0.3	2.0	24.0	12.0	67.79	0.0125	8,200	0.82	0.69	17.0
			8/4/05		22.8	24.0	1.5	1.0	24.0	12.0	135.58	0.0625	8,200	0.82	6.95	140.8
			9/29/05		11.0	24.0	1.0	1.0	24.0	12.0	135.58	0.0417	8,200	0.82	4.63	45.3
			Avg	1.5	20.4							Avg	8,200	Avg	4.1	67.7
13	23.7	20	6/30/05	0.6	1.6	36.0	2.0	1.0	24.0	12.0	135.58	0.0556	5,016	0.50	3.78	5.4
			8/4/05		1.7	36.0	1.0	1.0	24.0	12.0	135.58	0.0278	5,016	0.50	1.89	2.9
			9/29/05		3.3	36.0	0.6	1.0	24.0	12.0	135.58	0.0167	5,016	0.50	1.13	3.3
			Avg	0.6	2.2							Avg	5,016	Avg	2.3	3.8
14	24.5	xx	Clay												0.0	0.0
15	26.4	xx	Clay												0.0	0.0
16	28.0	xx	Clay												0.0	0.0
17	29.2	xx	Clay												0.0	0.0
18	31.2	xx	Clay												0.0	0.0

Table 5
Spreadsheet showing the phosphorus results and hydrological data and flow estimates for the SW Torch Lake piezometers.

	Peri.	Perp.														
	Dist.	Dist.	Date	Lake TP	Piez TP	dl	dh	T2-T1	H2	H1	K*(10**6)	dh/dl	S	A*(10**-6)	Q	TPQ
well #	(mi)	(ft.)		(ppb)	(ppb)	(in)	(in)	(s)	(in)	(in)	(ft/s)		(ft)	(ft^2)	(cfs)	(kg/yr)
19	32.0	40	6/25/05	1.0	25.4	72.0	3.0	2.0	24.0	12.0	67.79	0.0417	400	0.04	0.11	2.6
			8/4/05		28.8	72.0	2.5	2.0	24.0	12.0	67.79	0.0347	400	0.04	0.09	2.4
			9/29/05		10.9	72.0	2.0	2.0	24.0	12.0	67.79	0.0278	400	0.04	0.08	0.7
			Avg	1.0	21.7							Avg	400	AVG	0.1	1.9
	32.5	40	6/25/05		15.7	108.0	4.0	2.5	24.0	12.0	54.23	0.0370	400	0.04	0.08	1.1
			8/4/05	2.1	11.8	108.0	2.5	3.0	24.0	12.0	45.19	0.0231	400	0.04	0.04	0.4
			9/29/05		8.4	108.0	3.0	3.0	24.0	12.0	45.19	0.0278	400	0.04	0.05	0.4
			Avg	2.1	12.0							Avg	400	Avg	0.1	0.6
20	34.0	xx	Clay												0.0	0.0
21	34.8	xx	Clay												0.0	0.0
22	37.5	50	6/16/05	2.4	6.3	48.0	0.5	1.8	36.0	12.0	119.38	0.0104	7,900	0.79	0.98	5.5
			8/4/05	1.6	6.3	48.0	5.5	2.0	24.0	12.0	67.79	0.1146	7,900	0.79	6.14	34.4
			9/30/05		5.1	48.0	1.5	1.0	24.0	12.0	135.58	0.0313	7,900	0.79	3.35	15.2
			Avg	2.0	5.9							Avg	7,900	Avg	3.5	18.3
23	38.5	40	6/25/05	1.2	47.1	30.0	5.0	2.5	24.0	12.0	54.23	0.1667	10,600	1.06	9.58	401.0
			8/4/05		28.1	30.0	0.5	1.5	24.0	12.0	90.39	0.0167	10,600	1.06	1.60	39.9
			9/29/05		25.3	30.0	4.0	2.0	24.0	12.0	67.79	0.1333	10,600	1.06	9.58	215.4
			Avg	1.2	33.5							Avg	10,600	Avg	6.9	218.8
Total	40.5	mi	Avg	2.0	21.7	ppb						Total	23.1	mi Total	95.7	1,726.0
															cfs	kg/yr

Table 6
Spreadsheet showing the phosphorus results and hydrological data and flow estimates for the NW Torch Lake piezometers.

	Average	Range	Units
Lake TP Samples	2	0.6 - 4.4	ppb
Piezo TP Samples	21.7	1.6 - 72.1	ppb
Water Flow	95.7	0 - 27.0	cfs
TP Flow	1726	0 - 116	kg/y

Table 7
Summary of Tables 3 – 6. showing the average and range of the lake, piezometer, water and TP flows

well #	Perimeter Distance (mi)	Date	T lake (C)	T well (C)	SpC lake (mS/cm)	SpC well (mS/cm)	DO lake (mg/cm)	DO well (mg/cm)	pH lake	pH well
1	0.0	9/29/05	7.7	12.3	0.308	0.453	11.10	2.50	8.06	7.31
2	1.9	9/29/05	14.9	16.2	0.305	0.561	9.65	5.40	8.40	7.26
4	4.6	9/29/05	21.8	18.1	0.294	0.479	8.18	5.20	8.35	7.54
8	14.5	9/30/05	16.2	16.5	0.293	0.409	8.73	4.50	8.41	7.68
9	18.1	9/29/05	13.5	14.2	0.307	1.130	8.70	3.90	8.38	7.35
10	18.6	10/2/05	18.7	16.0	0.312	0.366	9.08	6.50	8.34	7.82
11	20.6	9/29/05	12.6	14.7	0.284	0.373	9.39	4.50	8.37	7.70
13	23.7	9/29/05	18.4	17.7	0.291	0.705	8.50	3.40	8.42	7.14
19	34.2	9/29/05	17.0	10.5	0.294	0.391	8.75	5.00	8.38	7.62
		9/29/05	17.0	11.0	0.294	0.381	8.75	5.00	8.38	7.65
22	37.5	9/30/05	15.1	16.7	0.297	0.444	9.32	6.77	8.37	7.55
23	39.5	9/29/05	12.4	16.5	0.300	0.512	10.00	3.86	8.16	7.34
Total	40.5	Avg	15.4	15.0	0.298	0.517	9.18	4.71	8.34	7.50

Table 8
Hydrolab data for the piezometer array on Torch Lake

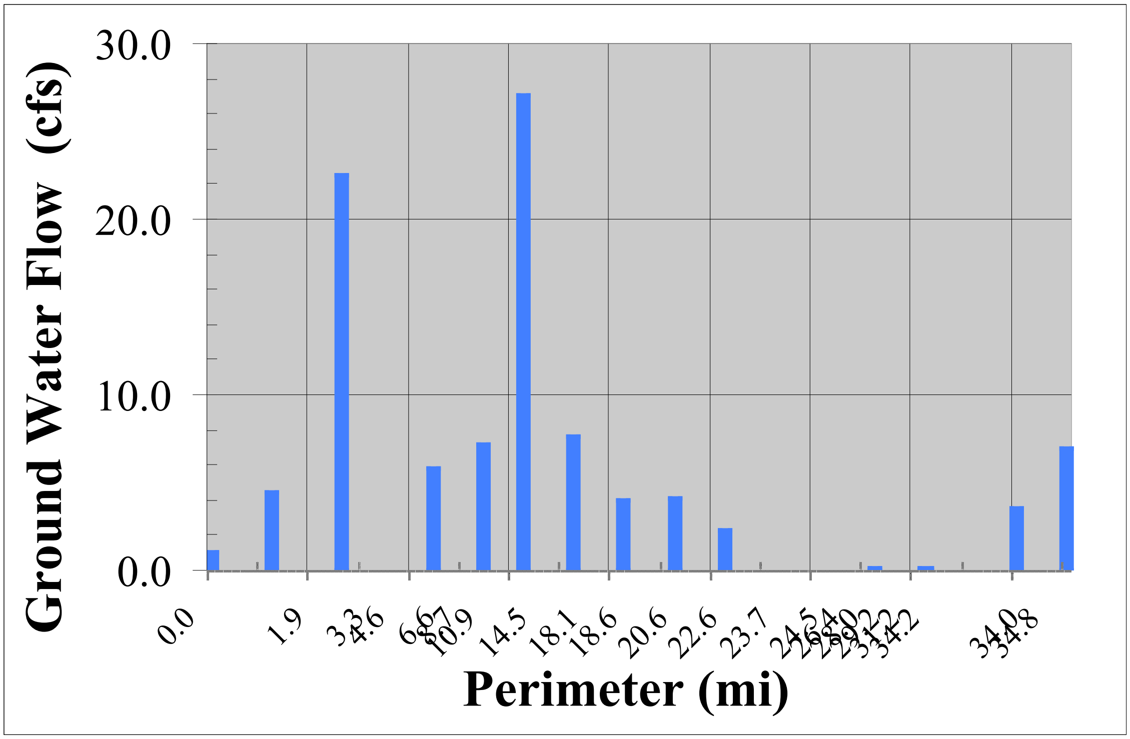


Fig. 10 Groundwater flow (cfs) versus Torch Lake perimeter clockwise starting with north central piezometer station #1.

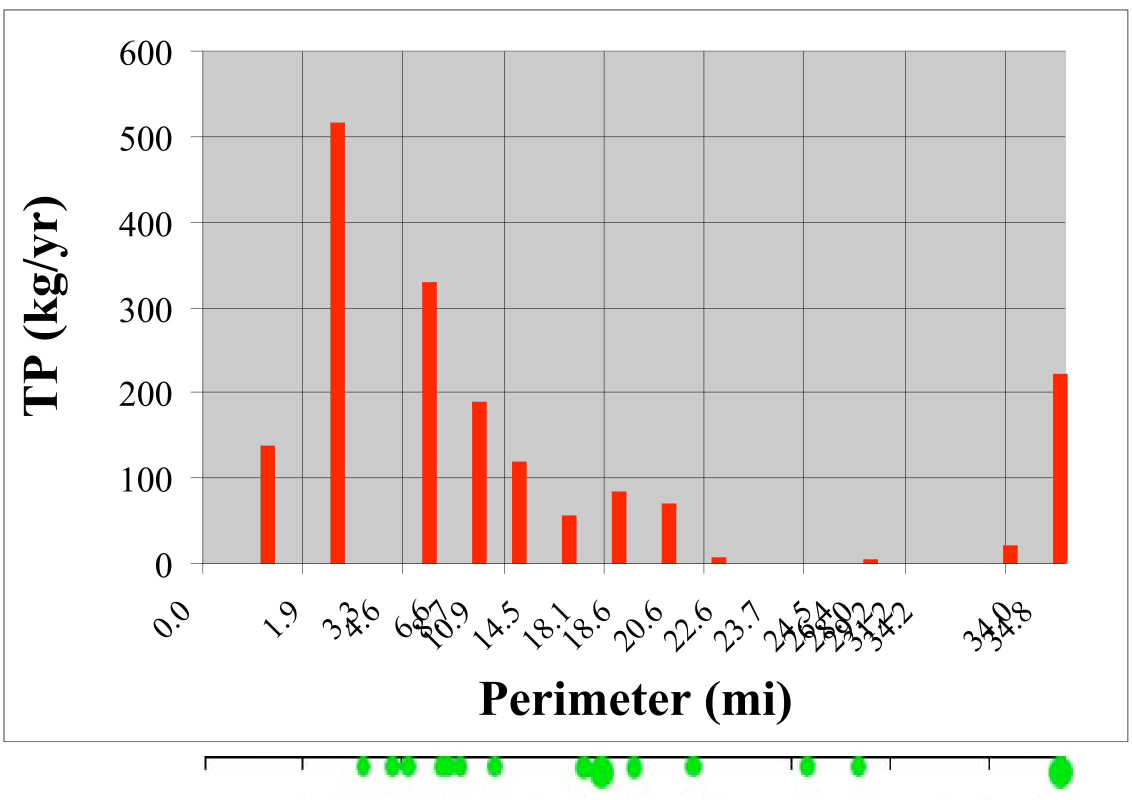


Fig. 11 Groundwater phosphorus flow (kg/yr) versus Torch Lake perimeter clockwise starting with north central piezometer station #1. Cladophora blooms are shown below.

Summary

Thirteen shallow piezometric wells were set around the periphery of Torch Lake in the summer of 2005. Measurements of the TP levels at these sites showed that the average was significantly higher than the lake itself and higher that that expected from natural sources. The lake level was found to be 2.0 ppb and the average piezometer level, 21.7 ppb. Measurements of the total ground water flow rate from these piezometers, as interpreted by well known pressure and conductivity analysis and with the assumption of a 100 ft flow region into the lake, found to be 95.7 cfs and the total phosphorus flow was 1726 kg/yr. The region which gave the highest phosphorus input was not correlated with significant cladophora blooms and had less, not more, human development. As these results are the first of their kind on Torch Lake, we await different or improved techniques to corroborate our results.

References:

[1] Quality Assurance Project Plan Characterization of Groundwater Discharge to Lake Whatcom by C. Pitz, Washington State Department of Ecology Environmental Assessment Program, Olympia, AS 98504-7710, Oct. 2002, Pub. No. 02-03-082.

[2] Project Plan: Characterization of Groundwater Phosphorus into Torch Lake by N. Bretz, D. Branson, T. Hannert, P. Roush, D. Endicott, May 2005.

[3] Development of a Predictive Nutrient-Based Water Quality Model for the Three Lakes System Year 1: Torch Lake, T. Hannert, D. Branson, M. DeGraeve and D. Endicott, Three Lakes Association and Great Lakes Environmental Center, 04 MDEQ grant PO# 761P40021 (June, 2004).

[4] Shoreline Algal Survey of Torch Lake, Clam Lake, and Lake Bellaire, by S. Conkle, B Lunn, J. Menestrina, N. Bretz, and T. Hannert, Three Lakes Association, PO Box 689, Bellaire, MI 49615

[5] Antrim County District Health Department records, 209 Portage Dr., Bellaire, MI 49615.

[6] Antrim County Land Use Atlas 1978-1998, Antrim County Publication in cooperation with The Land Information Access Assn.

[7] Michigan Inland Lakes and Their Watersheds: An Atlas by W.M. Marsh and T.E. Borton, Stewart-Jackson Printing Co., Flint, MI (1974).

[8] GLEC SOP Number: CHM 2001: STANDARD OPERATING PROCEDURE FOR THE DETERMINATION OF TOTAL PHOSPHORUS IN SURFACE WATER SAMPLES.

[9] Hydrolab Corp., 5600 Lindbergh Drive, Loveland, CO 80539.

[10] GLEC SOP Number: FLD 6002: STANDARD OPERATING PROCEDURE FOR USE OF THE HYDROLAB SURVEYOR II AND SURVEYOR 3 UNITS and Quanta Operating Manual, Feb. 2002. Hydrolab Corp., 5600 Lindbergh Drive, Loveland, CO 80539.

[11] M.J. Hvorslev, Time Lag in the Observation of Ground-Water Levels and Pressures, US Army Waterways Experimental Station, Vicksburg, MS (1949).

[12] A Method for Installing and Monitoring Piezometers in Beds of Surface Water, S.J. Welsh and D.R. Lee; Ground Water, Vol. 27, No. 1, p. 87 (1989).

[13] T.W. Lamb and R.V. Whitman, *Soil Mechanics*: John Wiley and Sons, Inc., NY, 1969.

[14] Hydrolab Quanta, Hach Environmental, PO Box 389, Loveland, CO, 80539.

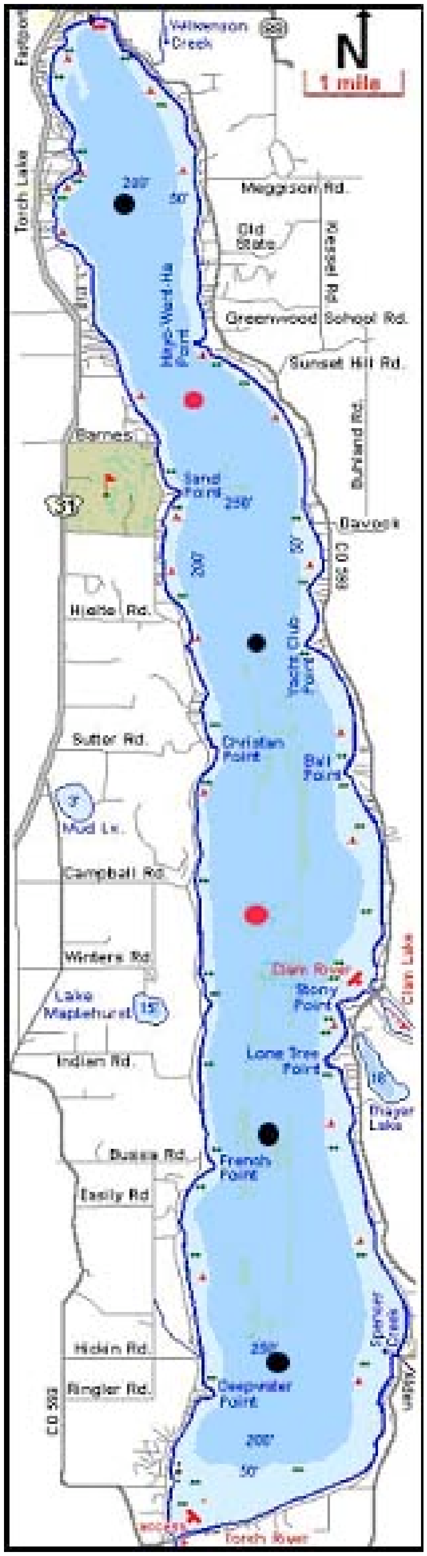
[15] Long Lake Nutrient and Hydologic Model prepared for the Long Lake Watershed Partnership, Jan. 2001 by R. Canale and P.M. McCool.

[16] Quantitative Trophic Reconstruction from Sedimentary Diatom Assemblages: A Cautionary Tale by S. Fritz, J. Kingston, D. Engstrom, Freshwater Biology (1993), **30,** 1-23

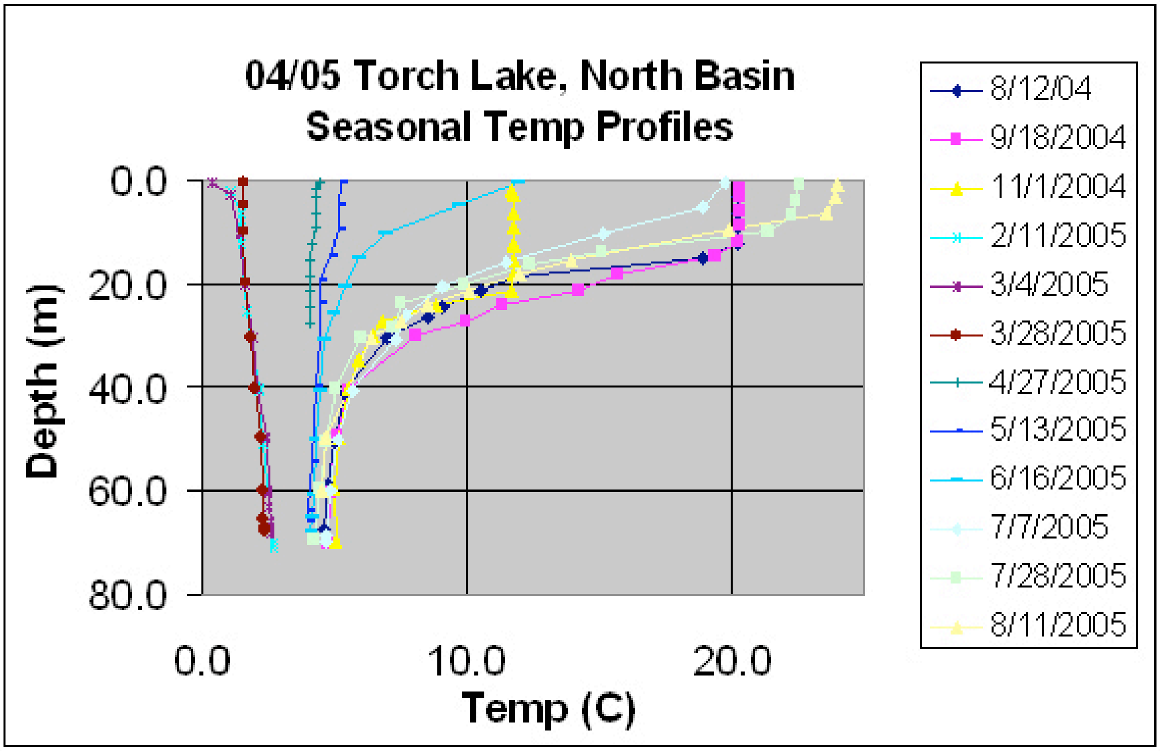
Appendix II

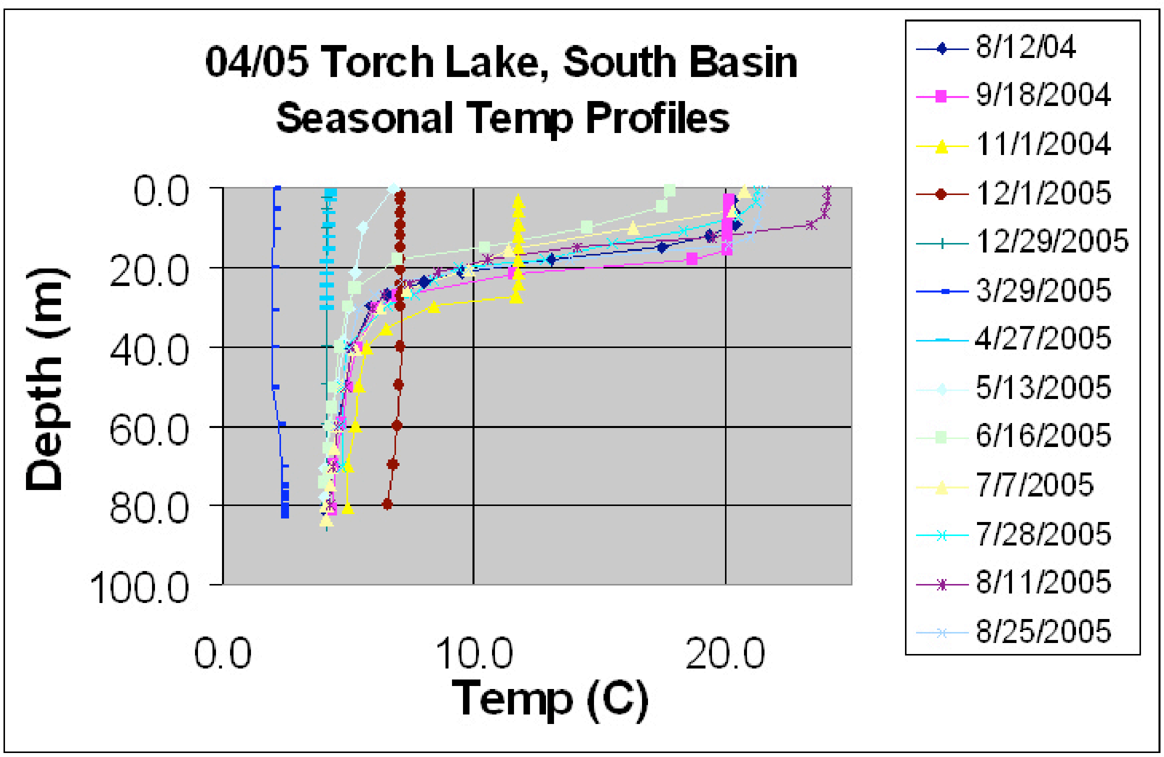
Seasonal Variations of Temperature, Dissolved Oxygen, pH, and Specific Conductivity in Torch Lake 2004-2005

Three Lakes Association
PO Box 689
Bellaire, MI 49615

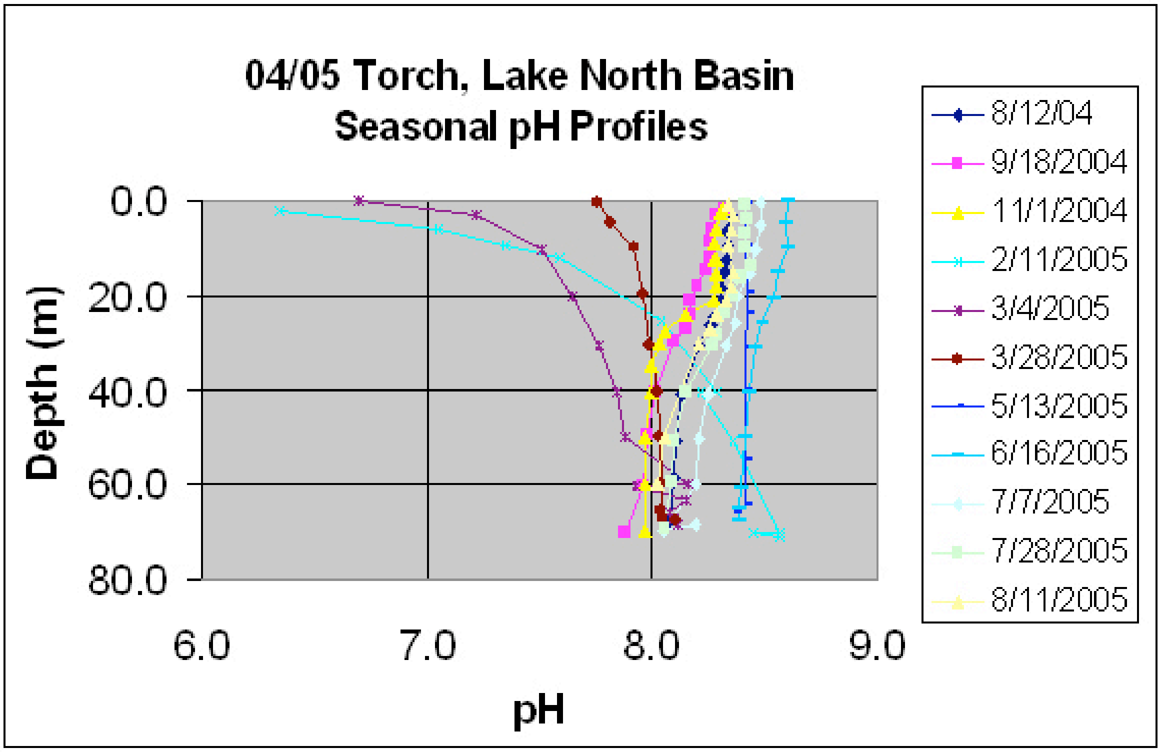


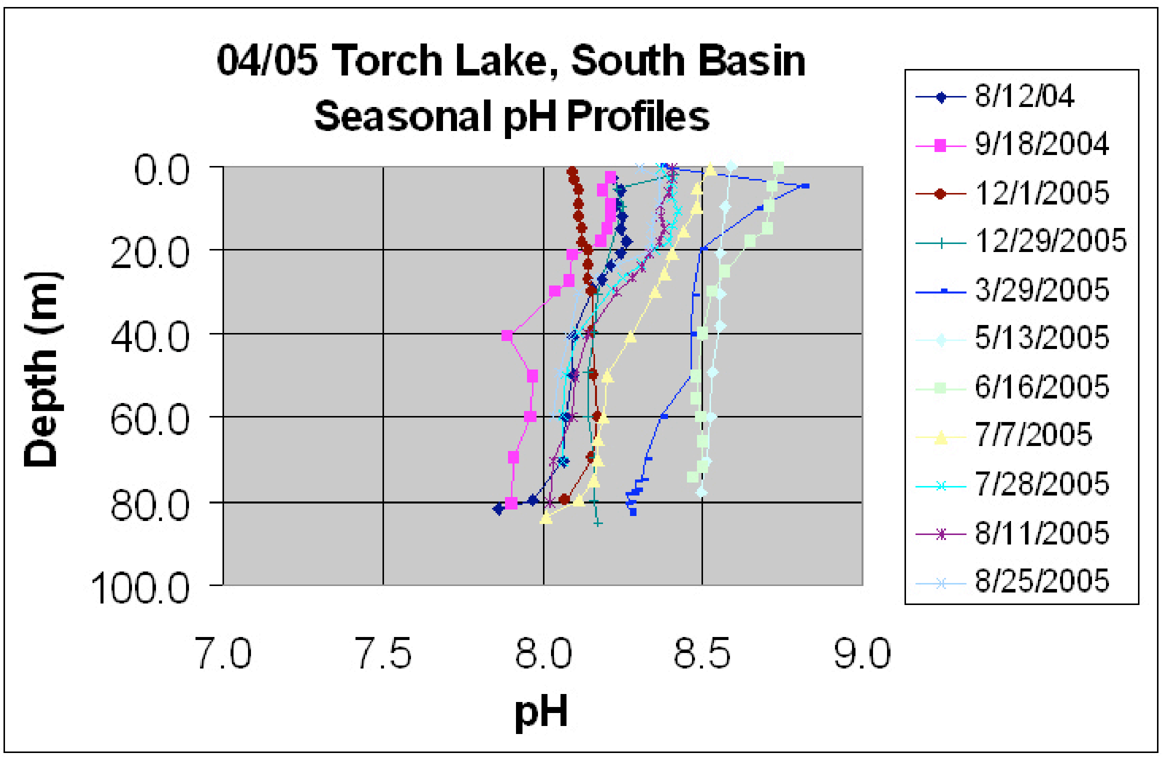
Map of Torch Lake showing north and south basin sampling locations in red.
South basin: W44^{o} 42.7", N85^{o} 18' 36.2"; North basin: W45^{o}2'24.2", N85^{o}19'25.9"
The black and red dots together show the north/south sampling set.



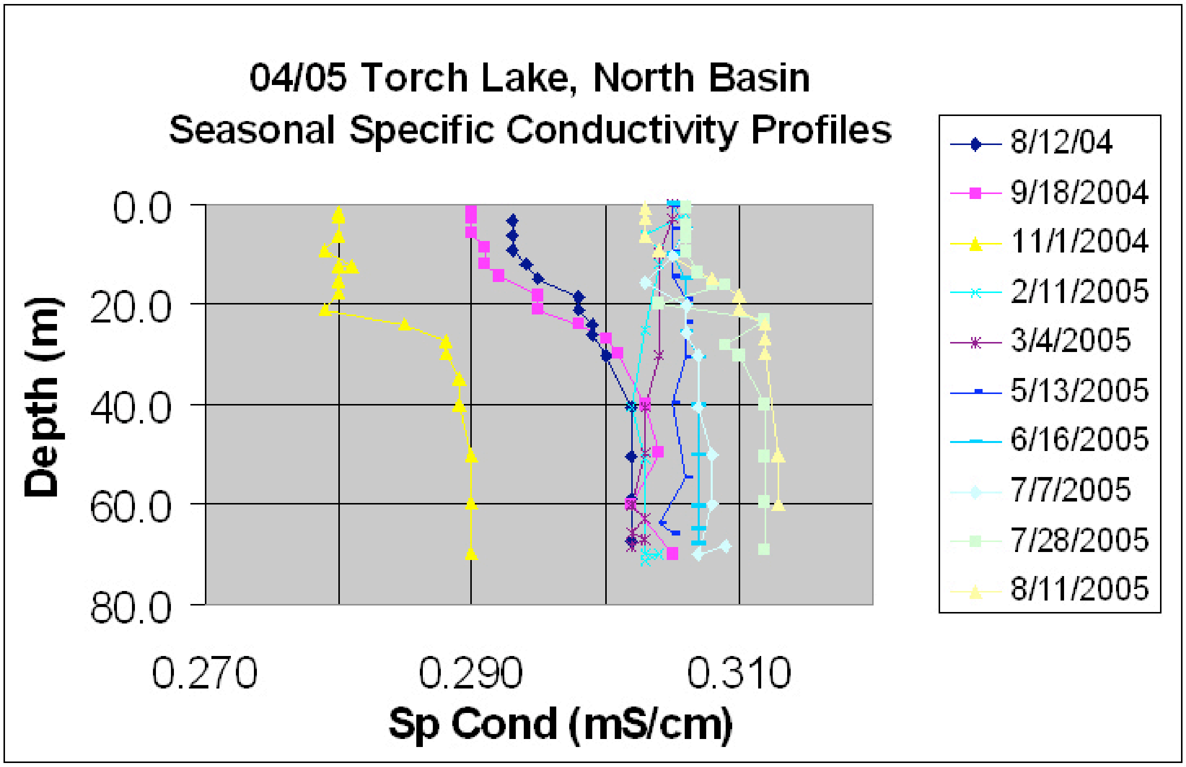


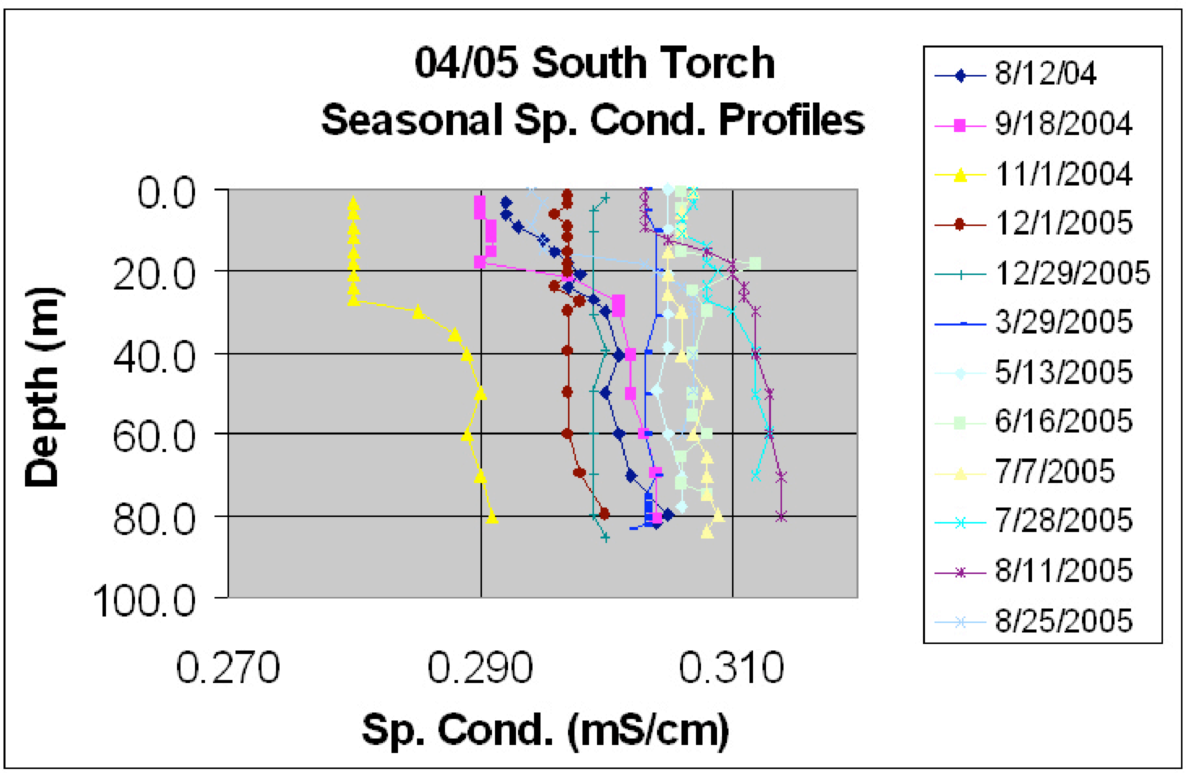
Seasonal temperature profiles from 2004/5 for the north and south Torch Lake basins



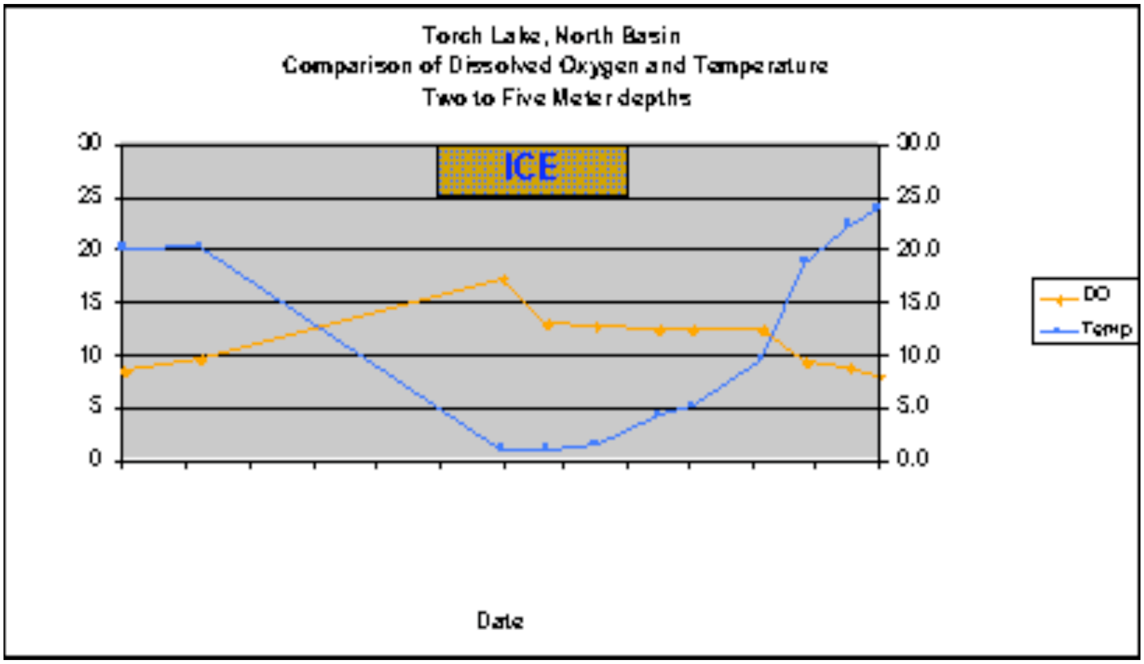


Seasonal pH profiles from 2004/5 for the north and south Torch Lake basins

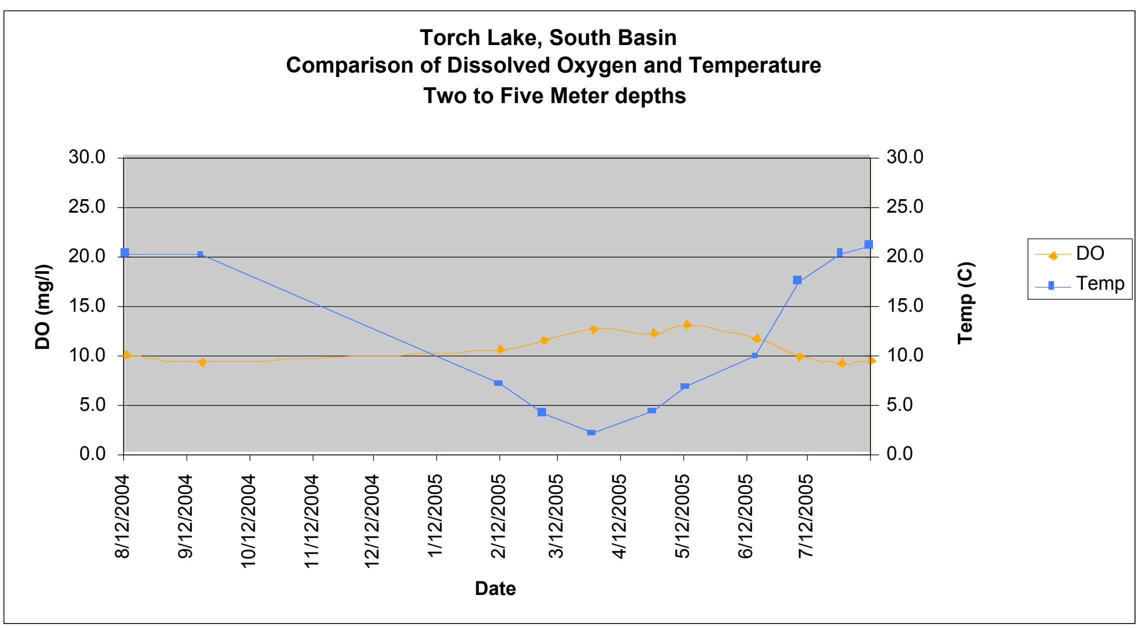




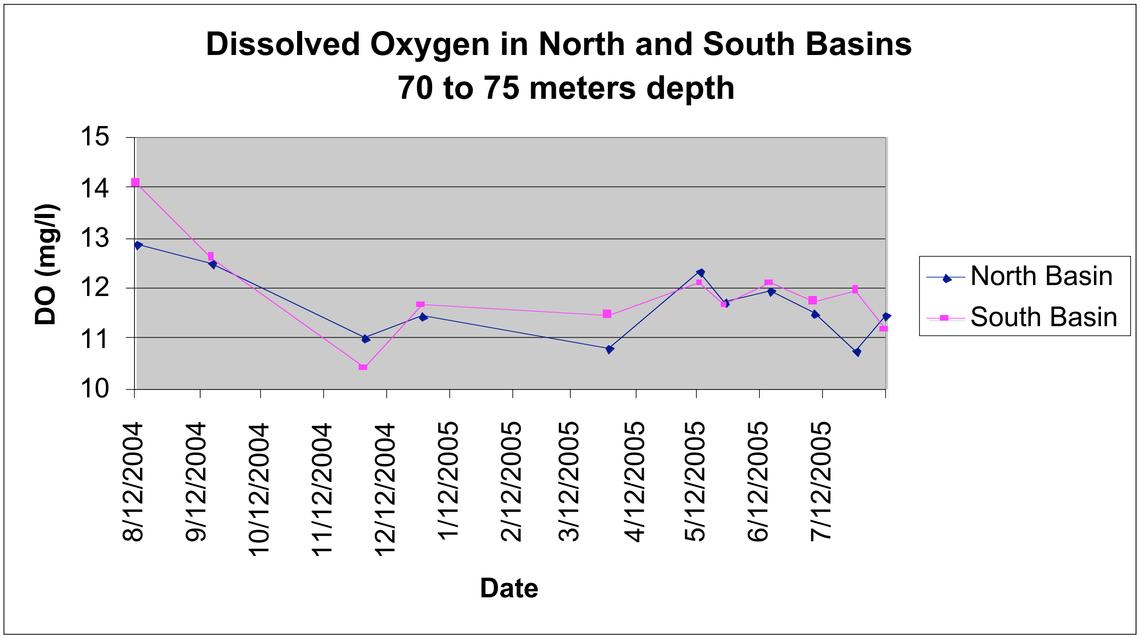
Seasonal specific conductivity profiles from 2004/5 for the north and south Torch Lake basins



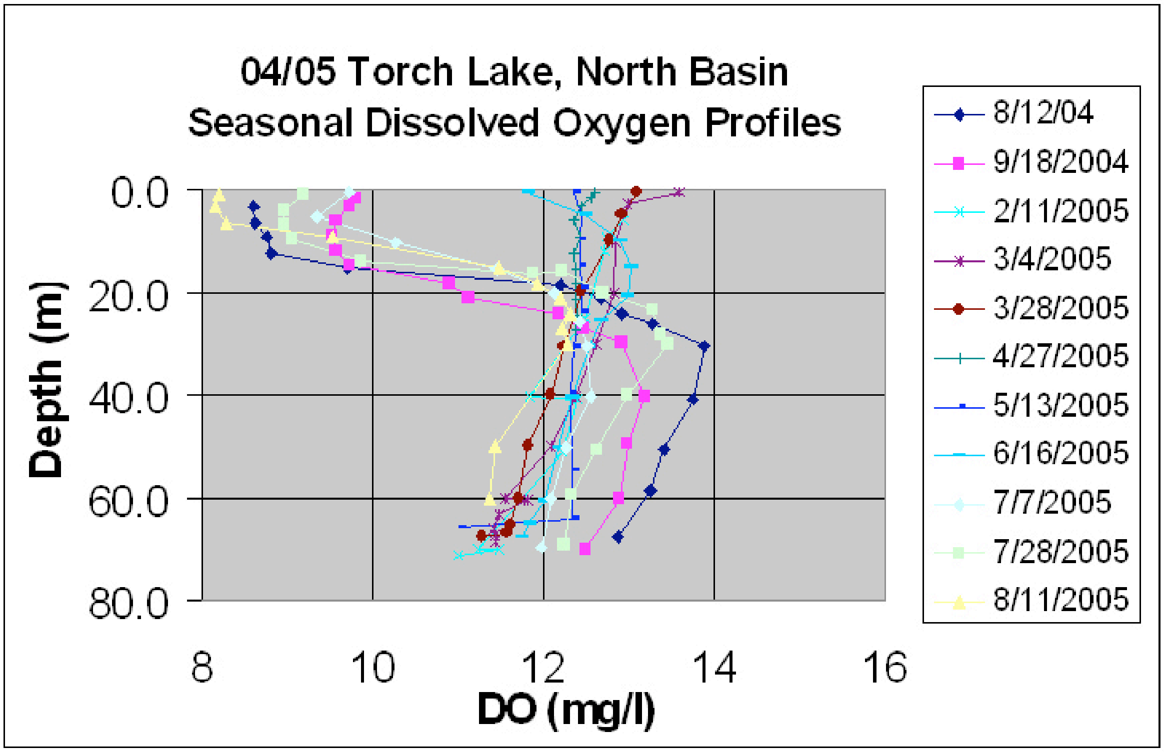
Dissolved oxygen seasonal changes in north basin at 2m and 5m depths

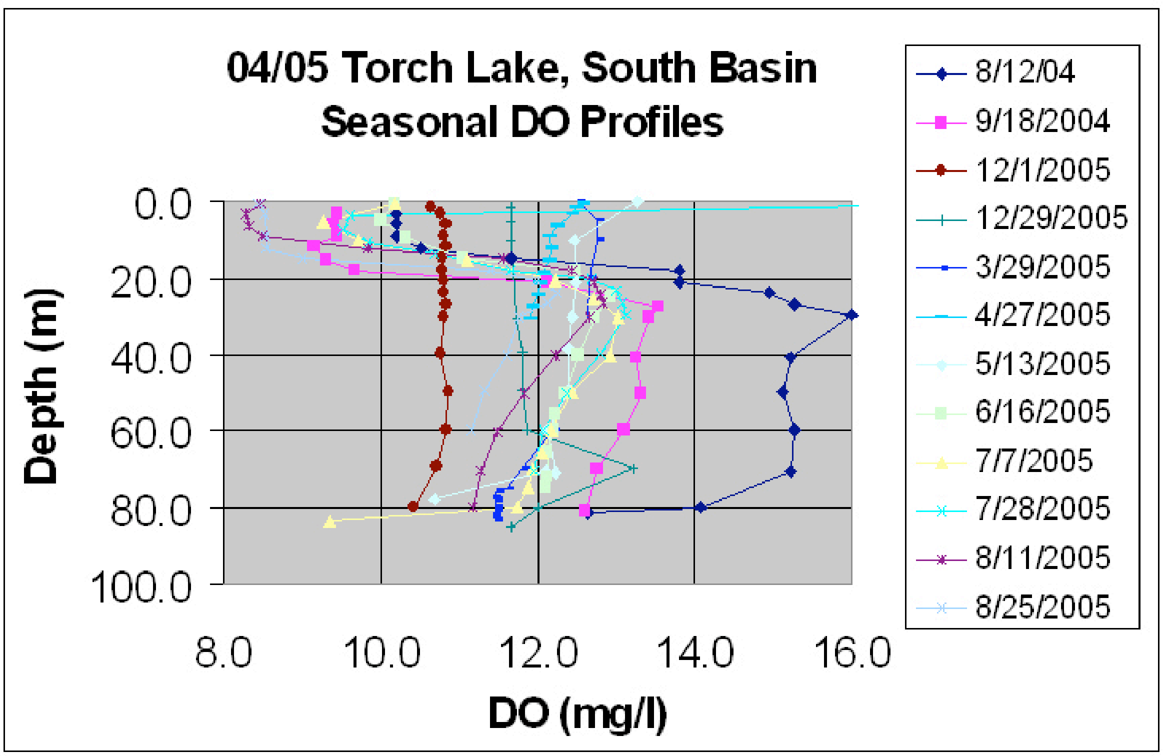


Dissolved oxygen seasonal changes in south basin at 2m and 5m depths

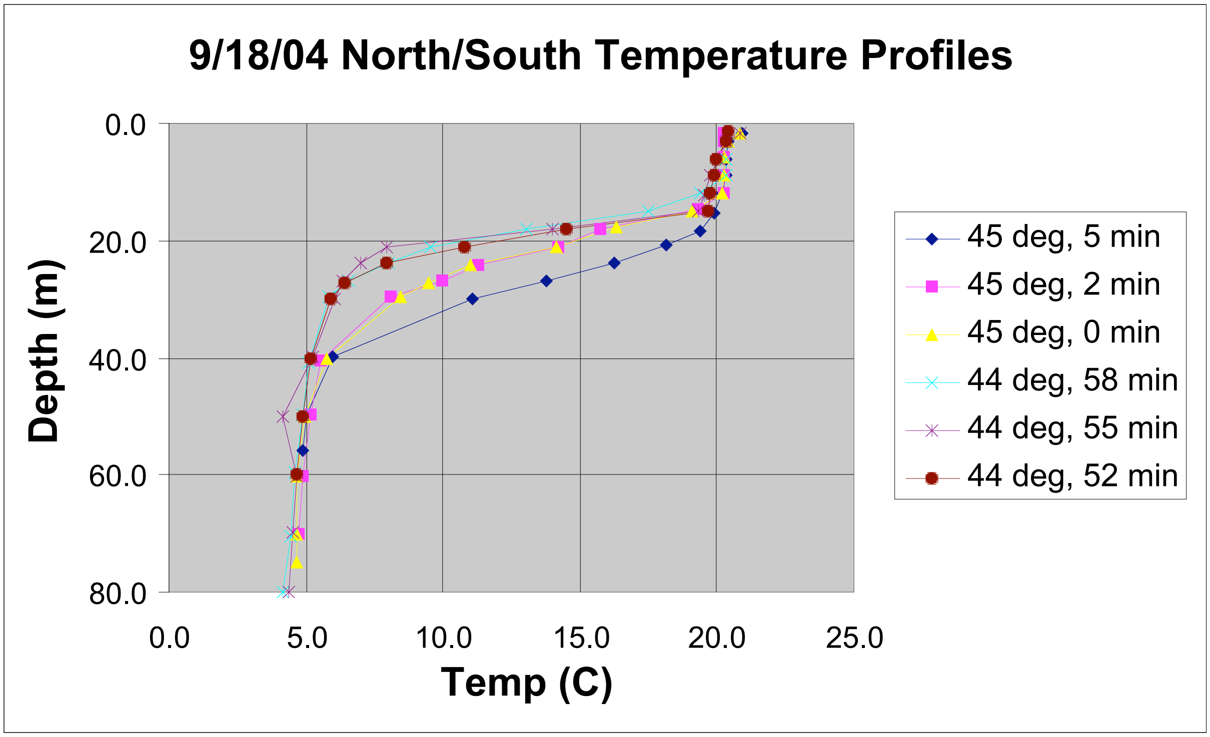


Seasonal changes in the dissolved oxygen in the north and south basins of Torch Lake at depths of 70-75 m

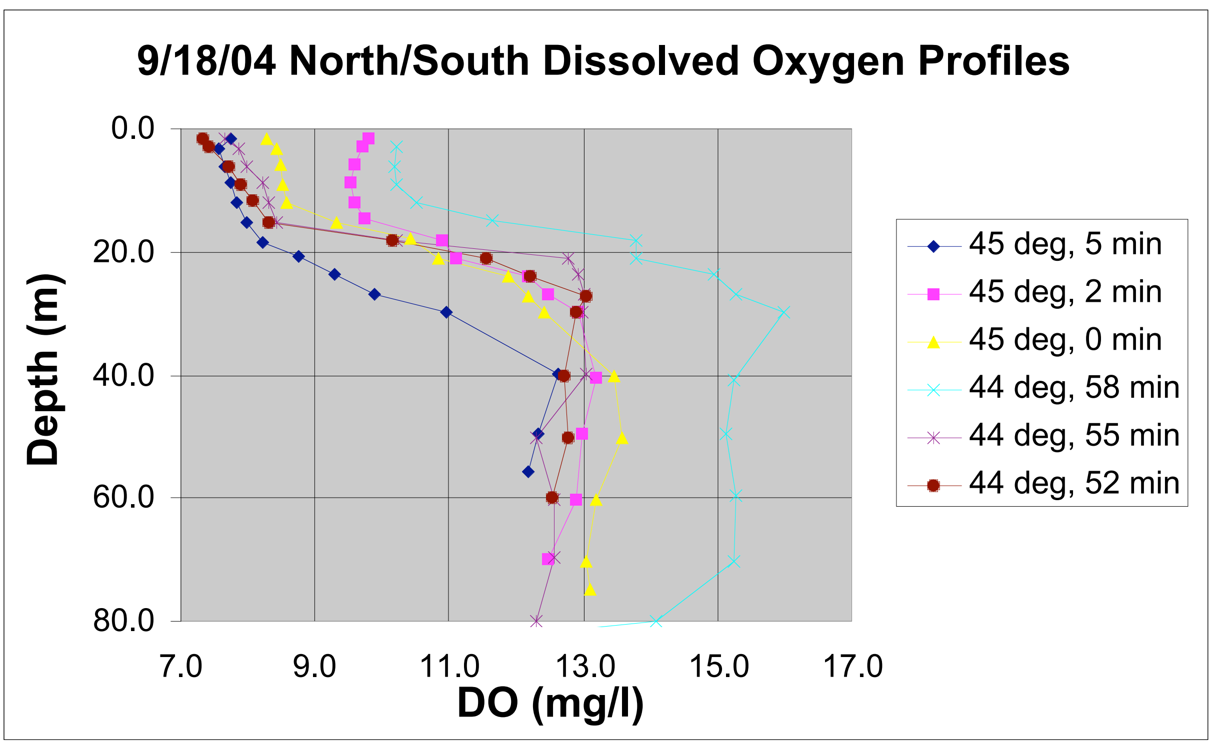




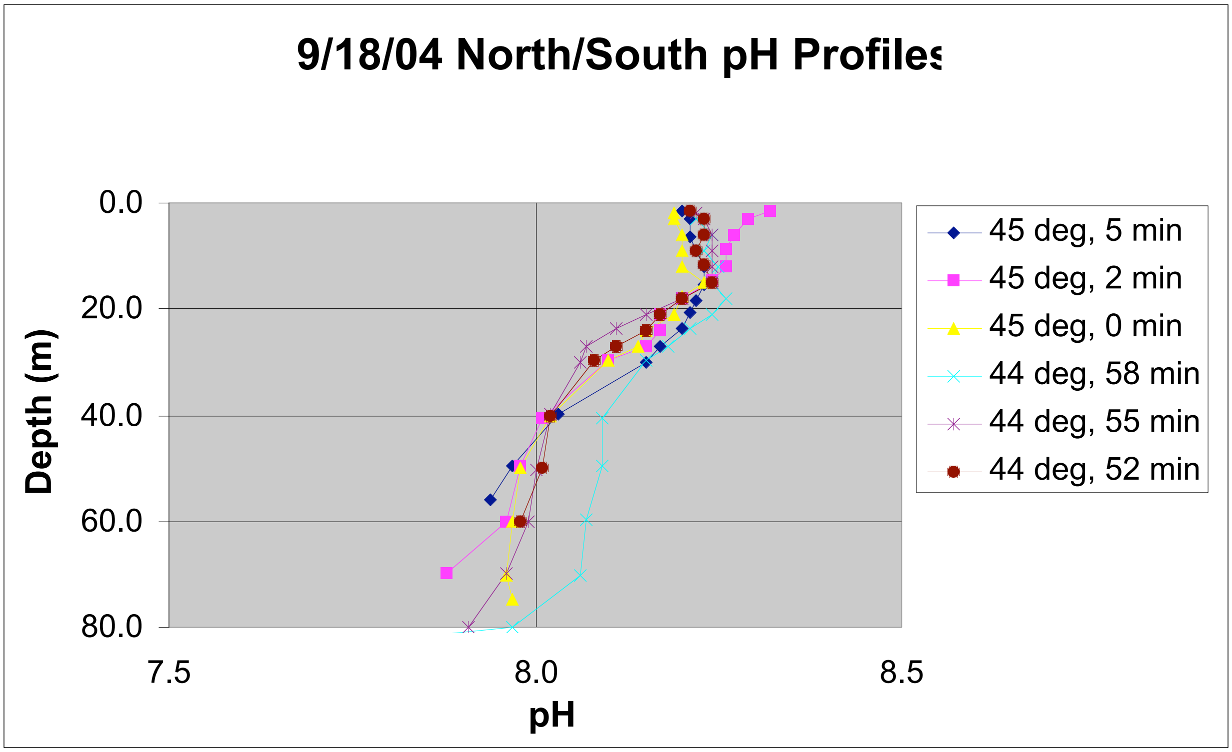
Seasonal dissolved oxygen profiles from 2004/5 for the north and south Torch Lake basins



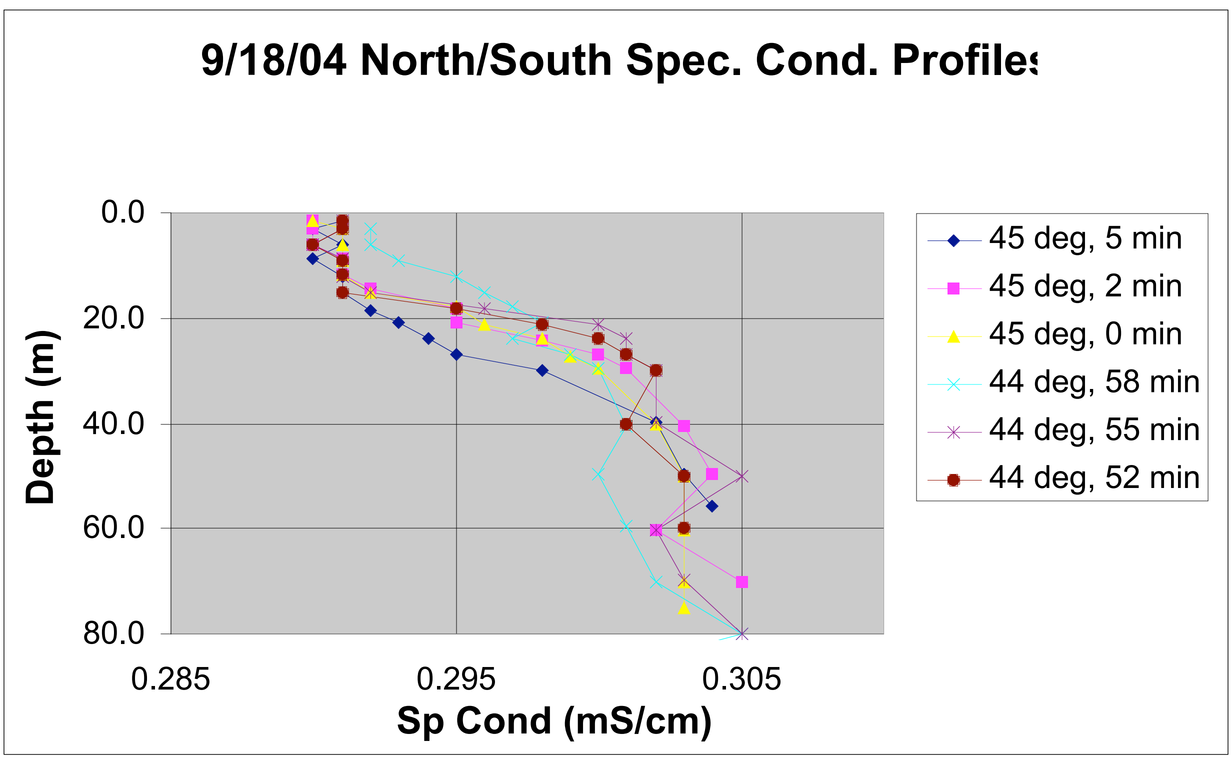
Temperature profiles in Torch Lake at six locations distributed on the north/south center.



Dissolved oxygen profiles in Torch Lake at six locations distributed on the north/south center.



pH profiles in Torch Lake at six locations distributed on the north/south center.



Specific Conductivity profiles in Torch Lake at six locations distributed on the north/south center.

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
8/12/2004	North	N=>45 deg, 02 min	3.2	20.2	8.61	8.4	0.293
8/12/2004	North	N=>45 deg, 02 min	6.4	20.2	8.62	8.3	0.293
8/12/2004	North	N=>45 deg, 02 min	9.2	20.2	8.76	8.3	0.293
8/12/2004	North	N=>45 deg, 02 min	12.2	20.2	8.82	8.3	0.294
8/12/2004	North	N=>45 deg, 02 min	15.0	18.9	9.71	8.3	0.295
8/12/2004	North	N=>45 deg, 02 min	18.5	12.0	12.21	8.3	0.298
8/12/2004	North	N=>45 deg, 02 min	21.0	10.6	12.68	8.3	0.298
8/12/2004	North	N=>45 deg, 02 min	24.2	9.1	12.92	8.3	0.299
8/12/2004	North	N=>45 deg, 02 min	26.3	8.5	13.28	8.3	0.299
8/12/2004	North	N=>45 deg, 02 min	30.3	7.0	13.88	8.2	0.300
8/12/2004	North	N=>45 deg, 02 min	40.7	5.4	13.76	8.1	0.302
8/12/2004	North	N=>45 deg, 02 min	50.7	5.0	13.41	8.1	0.302
8/12/2004	North	N=>45 deg, 02 min	58.8	4.8	13.25	8.1	0.302
8/12/2004	North	N=>45 deg, 02 min	67.6	4.6	12.87	8.1	0.302
8/12/2004	South	S=>44 deg, 58 min	3.0	20.3	10.2	8.2	0.292
8/12/2004	South	S=>44 deg, 58 min	6.0	20.3	10.2	8.2	0.292
8/12/2004	South	S=>44 deg, 58 min	9.0	20.3	10.2	8.2	0.293
8/12/2004	South	S=>44 deg, 58 min	12.0	19.4	10.5	8.3	0.295
8/12/2004	South	S=>44 deg, 58 min	15.0	17.5	11.7	8.2	0.296
8/12/2004	South	S=>44 deg, 58 min	18.0	13.1	13.8	8.3	0.297
8/12/2004	South	S=>44 deg, 58 min	21.0	9.5	13.8	8.2	0.298
8/12/2004	South	S=>44 deg, 58 min	23.7	8.0	15.0	8.2	0.297
8/12/2004	South	S=>44 deg, 58 min	26.9	6.5	15.3	8.2	0.299
8/12/2004	South	S=>44 deg, 58 min	29.7	5.8	16.0	8.2	0.300
8/12/2004	South	S=>44 deg, 58 min	40.7	5.1	15.2	8.1	0.301
8/12/2004	South	S=>44 deg, 58 min	49.7	4.9	15.1	8.1	0.300
8/12/2004	South	S=>44 deg, 58 min	59.7	4.6	15.3	8.1	0.301
8/12/2004	South	S=>44 deg, 58 min	70.3	4.4	15.2	8.1	0.302
8/12/2004	South	S=>44 deg, 58 min	79.9	4.1	14.1	8.0	0.305
8/12/2004	South	S=>44 deg, 58 min	81.6	4.1	12.6	7.9	0.304
9/18/2004	Middle	M=>45 deg, 00 min	1.7	20.8	8.3	8.2	0.290
9/18/2004	Middle	M=>45 deg, 00 min	3.1	20.4	8.4	8.2	0.291
9/18/2004	Middle	M=>45 deg, 00 min	5.9	20.3	8.5	8.2	0.291
9/18/2004	Middle	M=>45 deg, 00 min	9.0	20.3	8.5	8.2	0.291
9/18/2004	Middle	M=>45 deg, 00 min	11.9	20.2	8.6	8.2	0.291
9/18/2004	Middle	M=>45 deg, 00 min	15.1	19.1	9.3	8.2	0.292
9/18/2004	Middle	M=>45 deg, 00 min	17.7	16.4	10.4	8.2	0.295
9/18/2004	Middle	M=>45 deg, 00 min	21.2	14.1	10.8	8.2	0.296
9/18/2004	Middle	M=>45 deg, 00 min	24.0	11.0	11.9	8.2	0.298
9/18/2004	Middle	M=>45 deg, 00 min	27.2	9.5	12.2	8.1	0.299
9/18/2004	Middle	M=>45 deg, 00 min	29.7	8.5	12.4	8.1	0.300
9/18/2004	Middle	M=>45 deg, 00 min	40.1	5.7	13.5	8.0	0.302
9/18/2004	Middle	M=>45 deg, 00 min	50.1	5.0	13.6	8.0	0.303
9/18/2004	Middle	M=>45 deg, 00 min	60.2	4.7	13.2	8.0	0.303
9/18/2004	Middle	M=>45 deg, 00 min	70.2	4.6	13.0	8.0	0.303
9/18/2004	Middle	M=>45 deg, 00 min	74.9	4.6	13.1	8.0	0.303

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
9/18/2004	North	N=>45 deg, 02 min	1.6	20.3	9.8	8.3	0.290
9/18/2004	North	N=>45 deg, 02 min	3.0	20.3	9.7	8.3	0.290
9/18/2004	North	N=>45 deg, 02 min	5.9	20.3	9.6	8.3	0.290
9/18/2004	North	N=>45 deg, 02 min	8.7	20.3	9.5	8.3	0.291
9/18/2004	North	N=>45 deg, 02 min	11.9	20.3	9.6	8.3	0.291
9/18/2004	North	N=>45 deg, 02 min	14.5	19.4	9.7	8.2	0.292
9/18/2004	North	N=>45 deg, 02 min	18.1	15.7	10.9	8.2	0.295
9/18/2004	North	N=>45 deg, 02 min	21.0	14.2	11.1	8.2	0.295
9/18/2004	North	N=>45 deg, 02 min	24.1	11.3	12.2	8.2	0.298
9/18/2004	North	N=>45 deg, 02 min	27.0	10.0	12.5	8.2	0.300
9/18/2004	North	N=>45 deg, 02 min	29.7	8.1	12.9	8.1	0.301
9/18/2004	North	N=>45 deg, 02 min	40.4	5.5	13.2	8.0	0.303
9/18/2004	North	N=>45 deg, 02 min	49.6	5.1	13.0	8.0	0.304
9/18/2004	North	N=>45 deg, 02 min	60.2	4.9	12.9	8.0	0.302
9/18/2004	North	N=>45 deg, 02 min	70.0	4.7	12.5	7.9	0.305
9/18/2004	North-North	N=>45 deg, 05 min	1.6	20.9	7.7	8.2	0.291
9/18/2004	North-North	N=>45 deg, 05 min	3.1	20.4	7.6	8.2	0.290
9/18/2004	North-North	N=>45 deg, 05 min	6.2	20.3	7.7	8.2	0.291
9/18/2004	North-North	N=>45 deg, 05 min	8.9	20.3	7.8	8.2	0.290
9/18/2004	North-North	N=>45 deg, 05 min	12.0	20.2	7.8	8.2	0.291
9/18/2004	North-North	N=>45 deg, 05 min	15.3	19.9	8.0	8.2	0.291
9/18/2004	North-North	N=>45 deg, 05 min	18.5	19.4	8.2	8.2	0.292
9/18/2004	North-North	N=>45 deg, 05 min	20.7	18.1	8.8	8.2	0.293
9/18/2004	North-North	N=>45 deg, 05 min	23.8	16.3	9.3	8.2	0.294
9/18/2004	North-North	N=>45 deg, 05 min	27.0	13.7	9.9	8.2	0.295
9/18/2004	North-North	N=>45 deg, 05 min	29.9	11.1	11.0	8.2	0.298
9/18/2004	North-North	N=>45 deg, 05 min	39.9	6.0	12.6	8.0	0.302
9/18/2004	North-North	N=>45 deg, 05 min	49.7	5.1	12.3	8.0	0.303
9/18/2004	North-North	N=>45 deg, 05 min	55.8	4.9	12.2	7.9	0.304
9/18/2004	S1-South	S1-S=>44 deg, 55 min	1.7	20.8	7.7	8.2	0.291
9/18/2004	S1-South	S1-S=>44 deg, 55 min	3.1	20.3	7.9	8.2	0.291
9/18/2004	S1-South	S1-S=>44 deg, 55 min	6.1	20.0	8.0	8.2	0.290
9/18/2004	S1-South	S1-S=>44 deg, 55 min	8.9	19.7	8.2	8.2	0.291
9/18/2004	S1-South	S1-S=>44 deg, 55 min	12.1	19.5	8.3	8.2	0.291
9/18/2004	S1-South	S1-S=>44 deg, 55 min	15.1	19.3	8.4	8.2	0.292
9/18/2004	S1-South	S1-S=>44 deg, 55 min	18.2	14.0	10.2	8.2	0.296
9/18/2004	S1-South	S1-S=>44 deg, 55 min	21.2	7.9	12.8	8.2	0.300
9/18/2004	S1-South	S1-S=>44 deg, 55 min	23.7	7.0	12.9	8.1	0.301
9/18/2004	S1-South	S1-S=>44 deg, 55 min	27.0	6.3	13.0	8.1	0.301
9/18/2004	S1-South	S1-S=>44 deg, 55 min	29.9	6.0	13.0	8.1	0.302
9/18/2004	S1-South	S1-S=>44 deg, 55 min	39.9	5.2	13.0	8.0	0.302
9/18/2004	S1-South	S1-S=>44 deg, 55 min	50.2	4.2	12.3	8.0	0.305
9/18/2004	S1-South	S1-S=>44 deg, 55 min	60.2	4.7	12.6	8.0	0.302
9/18/2004	S1-South	S1-S=>44 deg, 55 min	69.7	4.5	12.6	8.0	0.303
9/18/2004	S1-South	S1-S=>44 deg, 55 min	80.1	4.4	12.3	7.9	0.305

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
9/18/2004	S2-South	S2-S=>44 deg. 52 min	1.5	20.4	7.3	8.2	0.291
9/18/2004	S2-South	S2-S=>44 deg. 52 min	3.0	20.3	7.4	8.2	0.291
9/18/2004	S2-South	S2-S=>44 deg. 52 min	6.1	20.0	7.7	8.2	0.290
9/18/2004	S2-South	S2-S=>44 deg. 52 min	9.0	19.9	7.9	8.2	0.291
9/18/2004	S2-South	S2-S=>44 deg. 52 min	11.8	19.8	8.1	8.2	0.291
9/18/2004	S2-South	S2-S=>44 deg. 52 min	15.1	19.7	8.3	8.2	0.291
9/18/2004	S2-South	S2-S=>44 deg. 52 min	18.2	14.5	10.2	8.2	0.295
9/18/2004	S2-South	S2-S=>44 deg. 52 min	21.2	10.8	11.5	8.2	0.298
9/18/2004	S2-South	S2-S=>44 deg. 52 min	23.9	7.9	12.2	8.2	0.300
9/18/2004	S2-South	S2-S=>44 deg. 52 min	27.1	6.4	13.1	8.1	0.301
9/18/2004	S2-South	S2-S=>44 deg. 52 min	29.8	5.9	12.9	8.1	0.302
9/18/2004	S2-South	S2-S=>44 deg. 52 min	40.1	5.2	12.7	8.0	0.301
9/18/2004	S2-South	S2-S=>44 deg. 52 min	50.1	4.9	12.8	8.0	0.303
9/18/2004	S2-South	S2-S=>44 deg. 52 min	60.0	4.7	12.6	8.0	0.303
9/18/2004	South	S=>44 deg, 58 min	3.0	20.1	9.4	8.2	0.290
9/18/2004	South	S=>44 deg, 58 min	6.0	20.1	9.4	8.2	0.290
9/18/2004	South	S=>44 deg, 58 min	9.1	20.1	9.4	8.2	0.291
9/18/2004	South	S=>44 deg, 58 min	11.9	20.0	9.1	8.2	0.291
9/18/2004	South	S=>44 deg, 58 min	15.2	20.0	9.3	8.2	0.291
9/18/2004	South	S=>44 deg, 58 min	18.0	18.7	9.7	8.2	0.290
9/18/2004	South	S=>44 deg, 58 min	21.3	11.6	12.1	8.1	0.297
9/18/2004	South	S=>44 deg, 58 min	27.3	7.0	13.5	8.1	0.301
9/18/2004	South	S=>44 deg, 58 min	30.1	6.1	13.4	8.0	0.301
9/18/2004	South	S=>44 deg, 58 min	40.5	5.3	13.3	7.9	0.302
9/18/2004	South	S=>44 deg, 58 min	50.1	5.0	13.3	8.0	0.302
9/18/2004	South	S=>44 deg, 58 min	59.7	4.7	13.1	8.0	0.303
9/18/2004	South	S=>44 deg, 58 min	69.6	4.4	12.8	7.9	0.304
9/18/2004	South	S=>44 deg, 58 min	80.9	4.4	12.6	7.9	0.304
11/1/2004	North	N=>45 deg, 05 min	1.8	11.7		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	2.6	11.8		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	6.1	11.8		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	9.1	11.8		8.3	0.279
11/1/2004	North	N=>45 deg, 05 min	12.3	11.8		8.3	0.281
11/1/2004	North	N=>45 deg, 05 min	12.5	11.8		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	15.4	11.8		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	18.0	11.8		8.3	0.280
11/1/2004	North	N=>45 deg, 05 min	21.1	11.7		8.3	0.279
11/1/2004	North	N=>45 deg, 05 min	24.0	8.9		8.2	0.285
11/1/2004	North	N=>45 deg, 05 min	27.2	6.9		8.1	0.288
11/1/2004	North	N=>45 deg, 05 min	29.8	6.5		8.0	0.288
11/1/2004	North	N=>45 deg, 05 min	34.7	5.9		8.0	0.289
11/1/2004	North	N=>45 deg, 05 min	40.0	5.6		8.0	0.289
11/1/2004	North	N=>45 deg, 05 min	50.0	5.2		8.0	0.290
11/1/2004	North	N=>45 deg, 05 min	59.8	5.0		8.0	0.290
11/1/2004	North	N=>45 deg, 05 min	69.8	5.0		8.0	0.290

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
11/1/2004	South	S=>44 deg, 58 min	3.0	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	5.7	11.8		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	8.9	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	9.1	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	11.9	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	15.0	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	18.0	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	20.9	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	24.1	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	27.0	11.7		8.3	0.280
11/1/2004	South	S=>44 deg, 58 min	29.9	8.4		8.1	0.285
11/1/2004	South	S=>44 deg, 58 min	35.3	6.5		8.0	0.288
11/1/2004	South	S=>44 deg, 58 min	40.1	5.7		8.0	0.289
11/1/2004	South	S=>44 deg, 58 min	49.9	5.4		8.0	0.290
11/1/2004	South	S=>44 deg, 58 min	60.0	5.3		8.0	0.289
11/1/2004	South	S=>44 deg, 58 min	69.9	4.9		8.0	0.290
11/1/2004	South	S=>44 deg, 58 min	80.3	5.0		8.0	0.291
12/1/2004	South	S=>44 deg, 58 min	1.6	7.1	10.6	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	3.3	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	5.9	7.1	10.8	8.1	0.296
12/1/2004	South	S=>44 deg, 58 min	9.2	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	11.9	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	15.0	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	18.2	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	20.4	7.1	10.8	8.1	0.297
12/1/2004	South	S=>44 deg, 58 min	23.9	7.1	10.8	8.1	0.296
12/1/2004	South	S=>44 deg, 58 min	27.2	7.1	10.8	8.1	0.298
12/1/2004	South	S=>44 deg, 58 min	29.9	7.1	10.8	8.2	0.297
12/1/2004	South	S=>44 deg, 58 min	39.8	7.1	10.8	8.2	0.297
12/1/2004	South	S=>44 deg, 58 min	49.9	7.0	10.9	8.2	0.297
12/1/2004	South	S=>44 deg, 58 min	60.0	7.0	10.8	8.2	0.297
12/1/2004	South	S=>44 deg, 58 min	69.5	6.8	10.7	8.2	0.298
12/1/2004	South	S=>44 deg, 58 min	79.8	6.6	10.4	8.1	0.300
12/29/2004	South	S=>44 deg, 58 min	1.8	4.1	11.7	8.4	0.300
12/29/2004	South	S=>44 deg, 58 min	5.3	4.1	11.7	8.2	0.299
12/29/2004	South	S=>44 deg, 58 min	9.9	4.1	11.7	8.3	0.299
12/29/2004	South	S=>44 deg, 58 min	30.5	4.1	11.7	8.2	0.299
12/29/2004	South	S=>44 deg, 58 min	39.4	4.2	11.8	8.2	0.300
12/29/2004	South	S=>44 deg, 58 min	49.4	4.1	11.8	8.1	0.299
12/29/2004	South	S=>44 deg, 58 min	59.7	4.1	11.9	8.1	0.299
12/29/2004	South	S=>44 deg, 58 min	69.7	4.1	13.2	8.2	0.299
12/29/2004	South	S=>44 deg, 58 min	79.7	4.1	12.0	8.2	0.299
12/29/2004	South	S=>44 deg, 58 min	85.1	4.1	11.7	8.2	0.300
2/11/2005	North	N=>45 deg, 05 min	2.0	1.1	17.4	6.4	0.306
2/11/2005	North	N=>45 deg, 05 min	6.1	1.5	13.0	7.1	0.303
2/11/2005	North	N=>45 deg, 05 min	9.2	1.5	12.7	7.4	0.304
2/11/2005	North	N=>45 deg, 05 min	12.0	1.6	12.7	7.6	0.304
2/11/2005	North	N=>45 deg, 05 min	25.1	1.7	12.5	8.0	0.303
2/11/2005	North	N=>45 deg, 05 min	40.5	2.2	11.8	8.3	0.302
2/11/2005	North	N=>45 deg, 05 min	40.6	2.2	12.4	8.2	0.302
2/11/2005	North	N=>45 deg, 05 min	51.1	2.3	12.2	8.4	0.303
2/11/2005	North	N=>45 deg, 05 min	70.0	2.7	11.2	8.6	0.303
2/11/2005	North	N=>45 deg, 05 min	70.2	2.7	11.5	8.5	0.304
2/11/2005	North	N=>45 deg, 05 min	71.1	2.7	11.0	8.6	0.303

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
3/4/2005	North	N=>45 deg, 05 min	0.2	0.4	13.6	6.7	0.305
3/4/2005	North	N=>45 deg, 05 min	2.9	1.1	13.0	7.2	0.305
3/4/2005	North	N=>45 deg, 05 min	10.1	1.5	12.9	7.5	0.304
3/4/2005	North	N=>45 deg, 05 min	20.0	1.7	12.8	7.7	0.304
3/4/2005	North	N=>45 deg, 05 min	30.2	2.0	12.6	7.8	0.304
3/4/2005	North	N=>45 deg, 05 min	40.5	2.1	12.4	7.8	0.303
3/4/2005	North	N=>45 deg, 05 min	49.9	2.5	12.1	7.9	0.303
3/4/2005	North	N=>45 deg, 05 min	60.0	2.5	11.5	8.2	0.302
3/4/2005	North	N=>45 deg, 05 min	60.4	2.5	11.8	7.9	0.302
3/4/2005	North	N=>45 deg, 05 min	63.2	2.6	11.5	8.2	0.303
3/4/2005	North	N=>45 deg, 05 min	66.0	2.6	11.4	8.1	0.302
3/4/2005	North	N=>45 deg, 05 min	67.3	2.6	11.4	8.1	0.303
3/4/2005	North	N=>45 deg, 05 min	68.4	2.6	11.4	8.1	0.302
3/28/2005	North	N=>45 deg, 05 min	0.5	1.6	13.1	7.8	0.340
3/28/2005	North	N=>45 deg, 05 min	4.9	1.6	12.9	7.8	0.340
3/28/2005	North	N=>45 deg, 05 min	9.9	1.6	12.8	7.9	0.341
3/28/2005	North	N=>45 deg, 05 min	19.8	1.7	12.5	8.0	0.340
3/28/2005	North	N=>45 deg, 05 min	30.3	1.9	12.2	8.0	0.340
3/28/2005	North	N=>45 deg, 05 min	40.0	2.1	12.1	8.0	0.339
3/28/2005	North	N=>45 deg, 05 min	50.0	2.2	11.8	8.0	0.339
3/28/2005	North	N=>45 deg, 05 min	60.0	2.3	11.7	8.0	0.340
3/28/2005	North	N=>45 deg, 05 min	65.3	2.3	11.6	8.0	0.340
3/28/2005	North	N=>45 deg, 05 min	67.0	2.4	11.6	8.1	0.340
3/28/2005	North	N=>45 deg, 05 min	67.7	2.4	11.3	8.1	0.340
3/28/2005	North	N=>45 deg, 05 min	69.0	2.4	10.8	8.0	0.340
3/29/2005	South	S=>44 deg, 58 min	0.2	2.0	12.5	8.4	0.303
3/29/2005	South	S=>44 deg, 58 min	5.0	2.1	12.8	8.8	0.303
3/29/2005	South	S=>44 deg, 58 min	10.1	2.0	12.8	8.7	0.304
3/29/2005	South	S=>44 deg, 58 min	20.0	2.0	12.7	8.5	0.304
3/29/2005	South	S=>44 deg, 58 min	30.8	2.0	12.6	8.5	0.304
3/29/2005	South	S=>44 deg, 58 min	40.0	2.0		8.5	0.303
3/29/2005	South	S=>44 deg, 58 min	50.0	2.0		8.5	0.303
3/29/2005	South	S=>44 deg, 58 min	59.7	2.2	12.2	8.4	0.303
3/29/2005	South	S=>44 deg, 58 min	70.0	2.3	11.8	8.3	0.304
3/29/2005	South	S=>44 deg, 58 min	75.1	2.4	11.6	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	75.5	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	77.1	2.4	11.4	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	78.0	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	78.3	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	78.5	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	80.0	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	80.9	2.4	11.5	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	82.1	2.4	11.4	8.3	0.303
3/29/2005	South	S=>44 deg, 58 min	83.1	2.4	11.5	8.3	0.302

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
4/27/2005	North	N=>45 deg, 05 min	0.3	4.5	12.6		
4/27/2005	North	N=>45 deg, 05 min	1.5	4.3	12.6		
4/27/2005	North	N=>45 deg, 05 min	3.1	4.3	12.5		
4/27/2005	North	N=>45 deg, 05 min	6.1	4.3	12.4		
4/27/2005	North	N=>45 deg, 05 min	9.2	4.3	12.4		
4/27/2005	North	N=>45 deg, 05 min	12.2	4.2	12.4		
4/27/2005	North	N=>45 deg, 05 min	15.3	4.1	12.4		
4/27/2005	North	N=>45 deg, 05 min	18.3	4.1	12.4		
4/27/2005	North	N=>45 deg, 05 min	21.4	4.1	12.4		
4/27/2005	North	N=>45 deg, 05 min	24.4	4.1	12.4		
4/27/2005	North	N=>45 deg, 05 min	27.5	4.1	12.4		
4/27/2005	North	N=>45 deg, 05 min	30.5	4.0	12.3		
4/27/2005	South	S=>44 deg, 58 min	0.3	4.3	12.58		
4/27/2005	South	S=>44 deg, 58 min	1.5	4.3	12.49		
4/27/2005	South	S=>44 deg, 58 min	3.1	4.3	12.43		
4/27/2005	South	S=>44 deg, 58 min	6.1	4.2	12.24		
4/27/2005	South	S=>44 deg, 58 min	9.2	4.2	12.15		
4/27/2005	South	S=>44 deg, 58 min	12.2	4.2	12.18		
4/27/2005	South	S=>44 deg, 58 min	15.3	4.2	12.14		
4/27/2005	South	S=>44 deg, 58 min	18.3	4.1	12.08		
4/27/2005	South	S=>44 deg, 58 min	21.4	4.1	12.02		
4/27/2005	South	S=>44 deg, 58 min	24.4	4.1	11.99		
4/27/2005	South	S=>44 deg, 58 min	27.5	4.1	11.93		
4/27/2005	South	S=>44 deg, 58 min	30.5	4.1	11.91		
5/13/2005	North	N=>45 deg, 05 min	0.5	5.3	12.37	8.41	0.305
5/13/2005	North	N=>45 deg, 05 min	4.9	5.2	12.45	8.41	0.305
5/13/2005	North	N=>45 deg, 05 min	9.6	5.2	12.43	8.41	0.305
5/13/2005	North	N=>45 deg, 05 min	14.7	4.8	12.43	8.42	0.305
5/13/2005	North	N=>45 deg, 05 min	19.1	4.5	12.44	8.42	0.306
5/13/2005	North	N=>45 deg, 05 min	23.7	4.5	12.45	8.42	0.306
5/13/2005	North	N=>45 deg, 05 min	30.6	4.5	12.36	8.41	0.306
5/13/2005	North	N=>45 deg, 05 min	39.6	4.3	12.32	8.41	0.305
5/13/2005	North	N=>45 deg, 05 min	54.6	4.2	12.34	8.41	0.306
5/13/2005	North	N=>45 deg, 05 min	64.0	4.1	12.34	8.41	0.304
5/13/2005	North	N=>45 deg, 05 min	65.8	4.0	8.33	8.37	0.305
5/13/2005	South	S=>44 deg, 58 min	0.1	6.8	13.26	8.59	0.305
5/13/2005	South	S=>44 deg, 58 min	9.8	5.5	12.47	8.57	0.305
5/13/2005	South	S=>44 deg, 58 min	20.9	5.3	12.48	8.55	0.305
5/13/2005	South	S=>44 deg, 58 min	30.4	5.0	12.44	8.55	0.305
5/13/2005	South	S=>44 deg, 58 min	38.4	4.8	12.39	8.55	0.305
5/13/2005	South	S=>44 deg, 58 min	49.2	4.6	12.4	8.53	0.304
5/13/2005	South	S=>44 deg, 58 min	59.9	4.2	12.13	8.52	0.305
5/13/2005	South	S=>44 deg, 58 min	70.7	4.1	12.21	8.51	0.306
5/13/2005	South	S=>44 deg, 58 min	70.6	4.1	12.1	8.51	0.306
5/13/2005	South	S=>44 deg, 58 min	77.8	4.1	10.68	8.49	0.306

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
5/25/2005	South	S=>44 deg, 58 min	0.5	11.2	11.7	8.5	0.306
5/25/2005	South	S=>44 deg, 58 min	5.2	9.9	11.8	8.6	0.306
5/25/2005	South	S=>44 deg, 58 min	10.3	9.1	12.0	8.6	0.306
5/25/2005	South	S=>44 deg, 58 min	15.2	6.6	12.5	8.6	0.307
5/25/2005	South	S=>44 deg, 58 min	20.1	6.0	12.5	8.6	0.307
5/25/2005	South	S=>44 deg, 58 min	25.0	5.6	12.5	8.6	0.306
5/25/2005	South	S=>44 deg, 58 min	30.2	5.3	12.5	8.5	0.308
5/25/2005	South	S=>44 deg, 58 min	40.0	4.8	12.4	8.5	0.308
5/25/2005	South	S=>44 deg, 58 min	50.1	4.5	12.3	8.5	0.308
5/25/2005	South	S=>44 deg, 58 min	59.9	4.3	12.3	8.5	0.308
5/25/2005	South	S=>44 deg, 58 min	70.1	4.2	12.2	8.5	0.307
5/25/2005	South	S=>44 deg, 58 min	79.6	4.0	11.9	8.5	0.308
5/25/2005	South	S=>44 deg, 58 min	83.3	4.0	11.7	8.5	0.308
6/16/2005	North	N=>45 deg, 05 min	0.2	12.0	11.8	8.6	0.305
6/16/2005	North	N=>45 deg, 05 min	4.9	9.7	12.5	8.6	0.306
6/16/2005	North	N=>45 deg, 05 min	10.0	6.9	12.9	8.6	0.305
6/16/2005	North	N=>45 deg, 05 min	15.0	6.0	13.0	8.6	0.306
6/16/2005	North	N=>45 deg, 05 min	20.4	5.4	13.0	8.5	0.306
6/16/2005	North	N=>45 deg, 05 min	25.5	5.0	12.7	8.5	0.306
6/16/2005	North	N=>45 deg, 05 min	30.6	4.7	12.5	8.5	0.307
6/16/2005	North	N=>45 deg, 05 min	40.4	4.5	12.3	8.4	0.307
6/16/2005	North	N=>45 deg, 05 min	50.2	4.3	12.2	8.4	0.307
6/16/2005	North	N=>45 deg, 05 min	60.7	4.3	12.0	8.4	0.307
6/16/2005	North	N=>45 deg, 05 min	65.0	4.2	11.9	8.4	0.307
6/16/2005	North	N=>45 deg, 05 min	67.8	4.1	11.8	8.4	0.307
6/16/2005	North	N=>45 deg, 05 min	69.8	4.1	11.7	8.4	0.308
6/16/2005	South	S=>44 deg, 58 min	0.7	17.8	10.2	8.7	0.306
6/16/2005	South	S=>44 deg, 58 min	4.6	17.5	10.0	8.7	0.306
6/16/2005	South	S=>44 deg, 58 min	9.7	14.5	10.3	8.7	0.306
6/16/2005	South	S=>44 deg, 58 min	15.0	10.4	11.1	8.7	0.306
6/16/2005	South	S=>44 deg, 58 min	18.1	7.0	12.5	8.7	0.312
6/16/2005	South	S=>44 deg, 58 min	24.9	5.2	12.9	8.6	0.307
6/16/2005	South	S=>44 deg, 58 min	29.9	5.0	12.7	8.5	0.308
6/16/2005	South	S=>44 deg, 58 min	40.2	4.7	12.5	8.5	0.307
6/16/2005	South	S=>44 deg, 58 min	50.1	4.4	12.4	8.5	0.307
6/16/2005	South	S=>44 deg, 58 min	55.4	4.3	12.2	8.5	0.307
6/16/2005	South	S=>44 deg, 58 min	60.0	4.3	12.2	8.5	0.308
6/16/2005	South	S=>44 deg, 58 min	65.5	4.2	12.1	8.5	0.306
6/16/2005	South	S=>44 deg, 58 min	71.9	4.2	12.1	8.5	0.306
6/16/2005	South	S=>44 deg, 58 min	74.6	4.1	12.1	8.5	0.308

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
7/7/2005	North	N=>45 deg, 05 min	0.4	19.7	9.7	8.5	0.306
7/7/2005	North	N=>45 deg, 05 min	5.0	18.9	9.4	8.5	0.306
7/7/2005	North	N=>45 deg, 05 min	10.3	15.2	10.3	8.5	0.305
7/7/2005	North	N=>45 deg, 05 min	15.6	11.5	11.5	8.4	0.303
7/7/2005	North	N=>45 deg, 05 min	20.2	9.1	12.1	8.4	0.306
7/7/2005	North	N=>45 deg, 05 min	25.8	7.7	12.4	8.4	0.306
7/7/2005	North	N=>45 deg, 05 min	30.4	7.3	12.5	8.3	0.307
7/7/2005	North	N=>45 deg, 05 min	40.5	5.7	12.6	8.3	0.307
7/7/2005	North	N=>45 deg, 05 min	50.3	5.1	12.3	8.2	0.308
7/7/2005	North	N=>45 deg, 05 min	60.1	4.9	12.1	8.2	0.308
7/7/2005	North	N=>45 deg, 05 min	69.9	4.7	12.0	8.1	0.307
7/7/2005	North	N=>45 deg, 05 min	68.6	4.7	8.6	8.2	0.309
7/7/2005	South	S=>44 deg, 58 min	0.3	20.7	10.2	8.5	0.307
7/7/2005	South	S=>44 deg, 58 min	5.5	20.3	9.3	8.5	0.306
7/7/2005	South	S=>44 deg, 58 min	9.9	16.3	9.7	8.5	0.306
7/7/2005	South	S=>44 deg, 58 min	15.3	11.4	11.1	8.4	0.305
7/7/2005	South	S=>44 deg, 58 min	20.6	9.7	12.2	8.4	0.305
7/7/2005	South	S=>44 deg, 58 min	25.5	7.3	12.7	8.4	0.305
7/7/2005	South	S=>44 deg, 58 min	30.1	6.3	13.0	8.4	0.306
7/7/2005	South	S=>44 deg, 58 min	40.4	5.2	12.9	8.3	0.306
7/7/2005	South	S=>44 deg, 58 min	49.9	4.8	12.5	8.2	0.308
7/7/2005	South	S=>44 deg, 58 min	59.9	4.5	12.2	8.2	0.307
7/7/2005	South	S=>44 deg, 58 min	65.4	4.4	12.1	8.2	0.308
7/7/2005	South	S=>44 deg, 58 min	70.1	4.3	11.9	8.2	0.308
7/7/2005	South	S=>44 deg, 58 min	74.8	4.3	11.9	8.2	0.308
7/7/2005	South	S=>44 deg, 58 min	79.9	4.1	11.7	8.1	0.309
7/7/2005	South	S=>44 deg, 58 min	83.7	4.1	9.3	8.0	0.308
7/28/2005	North	N=>45 deg, 05 min	0.8	22.6	9.2	8.4	0.306
7/28/2005	North	N=>45 deg, 05 min	4.0	22.4	9.0	8.4	0.306
7/28/2005	North	N=>45 deg, 05 min	6.8	22.3	9.0	8.4	0.306
7/28/2005	North	N=>45 deg, 05 min	9.7	21.4	9.1	8.4	0.306
7/28/2005	North	N=>45 deg, 05 min	13.7	15.1	9.9	8.4	0.307
7/28/2005	North	N=>45 deg, 05 min	16.2	12.4	11.9	8.4	0.308
7/28/2005	North	N=>45 deg, 05 min	16.0	12.4	12.2	8.4	0.309
7/28/2005	North	N=>45 deg, 05 min	20.0	9.9	12.7	8.4	0.304
7/28/2005	North	N=>45 deg, 05 min	23.4	7.5	13.3	8.3	0.312
7/28/2005	North	N=>45 deg, 05 min	28.2	7.3	13.4	8.3	0.309
7/28/2005	North	N=>45 deg, 05 min	30.2	6.0	13.5	8.3	0.310
7/28/2005	North	N=>45 deg, 05 min	40.0	5.1	13.0	8.2	0.312
7/28/2005	North	N=>45 deg, 05 min	50.7	4.7	12.6	8.1	0.312
7/28/2005	North	N=>45 deg, 05 min	59.5	4.5	12.3	8.1	0.312
7/28/2005	North	N=>45 deg, 05 min	69.3	4.2	12.3	8.1	0.312
7/28/2005	North	N=>45 deg, 05 min	79.9	4.1	11.5	7.9	0.314

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
7/28/2005	South	S=>44 deg, 58 min	0.6	21.3	17.5	8.4	0.307
7/28/2005	South	S=>44 deg, 58 min	3.8	21.2	9.6	8.4	0.307
7/28/2005	South	S=>44 deg, 58 min	7.3	20.5	9.5	8.4	0.306
7/28/2005	South	S=>44 deg, 58 min	10.6	18.3	9.8	8.4	0.306
7/28/2005	South	S=>44 deg, 58 min	13.9	15.5	10.7	8.4	0.308
7/28/2005	South	S=>44 deg, 58 min	17.8	12.8	11.7	8.4	0.308
7/28/2005	South	S=>44 deg, 58 min	20.0	9.4	12.7	8.4	0.309
7/28/2005	South	S=>44 deg, 58 min	23.1	8.4	13.0	8.3	0.308
7/28/2005	South	S=>44 deg, 58 min	26.7	7.6	13.1	8.3	0.308
7/28/2005	South	S=>44 deg, 58 min	29.7	6.6	13.1	8.2	0.310
7/28/2005	South	S=>44 deg, 58 min	39.7	5.0	12.8	8.1	0.312
7/28/2005	South	S=>44 deg, 58 min	50.0	4.8	12.4	8.1	0.312
7/28/2005	South	S=>44 deg, 58 min	59.6	4.8	12.1	8.1	0.313
7/28/2005	South	S=>44 deg, 58 min	70.3	4.7	12.0	8.1	0.312
8/11/2005	North	N=>45 deg, 05 min	0.8	24.0	8.2	8.3	0.303
8/11/2005	North	N=>45 deg, 05 min	3.0	24.0	8.2	8.4	0.303
8/11/2005	North	N=>45 deg, 05 min	6.2	23.6	8.3	8.4	0.303
8/11/2005	North	N=>45 deg, 05 min	9.3	19.9	9.5	8.3	0.304
8/11/2005	North	N=>45 deg, 05 min	15.1	13.9	11.5	8.4	0.308
8/11/2005	North	N=>45 deg, 05 min	18.1	12.0	11.9	8.4	0.310
8/11/2005	North	N=>45 deg, 05 min	21.0	10.2	12.2	8.3	0.310
8/11/2005	North	N=>45 deg, 05 min	24.1	8.5	12.3	8.3	0.312
8/11/2005	North	N=>45 deg, 05 min	26.9	7.5	12.2	8.3	0.312
8/11/2005	North	N=>45 deg, 05 min	30.0	6.4	12.3	8.2	0.312
8/11/2005	North	N=>45 deg, 05 min	50.0	4.7	11.4	8.1	0.313
8/11/2005	North	N=>45 deg, 05 min	60.0	4.6	11.4	8.0	0.313
8/11/2005	North	N=>45 deg, 05 min	70.1	4.4	10.8	8.0	0.314
8/11/2005	South	S=>44 deg, 58 min	0.4	24.0	8.5	8.4	0.303
8/11/2005	South	S=>44 deg, 58 min	3.1	24.0	8.3	8.4	0.303
8/11/2005	South	S=>44 deg, 58 min	6.1	24.0	8.3	8.4	0.303
8/11/2005	South	S=>44 deg, 58 min	9.1	23.4	8.5	8.4	0.303
8/11/2005	South	S=>44 deg, 58 min	12.1	19.4	9.8	8.4	0.305
8/11/2005	South	S=>44 deg, 58 min	15.0	14.1	11.6	8.4	0.308
8/11/2005	South	S=>44 deg, 58 min	18.1	10.5	12.4	8.4	0.310
8/11/2005	South	S=>44 deg, 58 min	21.0	8.5	12.7	8.3	0.310
8/11/2005	South	S=>44 deg, 58 min	24.1	7.4	12.8	8.3	0.311
8/11/2005	South	S=>44 deg, 58 min	26.6	6.4	12.8	8.3	0.311
8/11/2005	South	S=>44 deg, 58 min	30.0	5.9	12.7	8.2	0.312
8/11/2005	South	S=>44 deg, 58 min	40.1	5.1	12.2	8.1	0.312
8/11/2005	South	S=>44 deg, 58 min	50.1	4.9	11.8	8.1	0.313
8/11/2005	South	S=>44 deg, 58 min	60.1	4.5	11.5	8.1	0.313
8/11/2005	South	S=>44 deg, 58 min	70.5	4.4	11.3	8.0	0.314
8/11/2005	South	S=>44 deg, 58 min	80.0	4.3	11.2	8.0	0.314

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
8/25/2005	North	N=>45 deg, 05 min	0.1	21.7	8.5	8.5	0.294
8/25/2005	North	N=>45 deg, 05 min	3.0	21.7	8.5	8.4	0.293
8/25/2005	North	N=>45 deg, 05 min	6.0	21.4	8.6	8.4	0.294
8/25/2005	North	N=>45 deg, 05 min	9.0	21.2	8.5	8.4	0.294
8/25/2005	North	N=>45 deg, 05 min	11.9	20.3	9.1	8.4	0.295
8/25/2005	North	N=>45 deg, 05 min	14.9	16.8	10.8	8.3	0.300
8/25/2005	North	N=>45 deg, 05 min	18.0	13.3	11.7	8.3	0.302
8/25/2005	North	N=>45 deg, 05 min	21.0	10.0	12.3	8.3	0.305
8/25/2005	North	N=>45 deg, 05 min	23.9	7.6	12.4	8.3	0.305
8/25/2005	North	N=>45 deg, 05 min	27.0	6.1	12.5	8.2	0.306
8/25/2005	North	N=>45 deg, 05 min	30.0	5.5	12.3	8.2	0.307
8/25/2005	North	N=>45 deg, 05 min	40.0	4.9	12.1	8.1	0.308
8/25/2005	North	N=>45 deg, 05 min	48.9	4.8	11.6	8.1	0.307
8/25/2005	North	N=>45 deg, 05 min	60.1	4.6	11.5	8.1	0.307
8/25/2005	North	N=>45 deg, 05 min	67.6	4.3	6.8	7.9	0.309
8/25/2005	South	S=>44 deg, 58 min	0.3	21.5	8.5	8.3	0.294
8/25/2005	South	S=>44 deg, 58 min	3.0	21.5	8.5	8.4	0.295
8/25/2005	South	S=>44 deg, 58 min	8.8	21.3	8.5	8.4	0.294
8/25/2005	South	S=>44 deg, 58 min	12.1	21.0	8.5	8.4	0.295
8/25/2005	South	S=>44 deg, 58 min	14.6	20.1	9.0	8.3	0.295
8/25/2005	South	S=>44 deg, 58 min	18.1	13.8	11.4	8.3	0.303
8/25/2005	South	S=>44 deg, 58 min	20.5	9.8	12.0	8.3	0.304
8/25/2005	South	S=>44 deg, 58 min	23.8	7.1	12.3	8.2	0.306
8/25/2005	South	S=>44 deg, 58 min	26.7	6.0	12.1	8.2	0.307
8/25/2005	South	S=>44 deg, 58 min	30.1	5.4	11.8	8.1	0.307
8/25/2005	South	S=>44 deg, 58 min	40.4	5.0	11.6	8.1	0.307
8/25/2005	South	S=>44 deg, 58 min	49.2	4.7	11.3	8.1	0.307
8/25/2005	South	S=>44 deg, 58 min	60.0	4.5	11.1	8.0	0.306
8/25/2005	South	S=>44 deg, 58 min	69.9	4.4	11.1	8.0	0.308
9/8/2005	North	N=>45 deg, 05 min	0.4	20.9	10.3	7.7	0.294
9/8/2005	North	N=>45 deg, 05 min	2.9	20.9	8.9	8.1	0.294
9/8/2005	North	N=>45 deg, 05 min	6.2	20.9	8.7	8.2	0.294
9/8/2005	North	N=>45 deg, 05 min	8.8	20.8	8.6	8.3	0.295
9/8/2005	North	N=>45 deg, 05 min	12.0	20.8	8.6	8.3	0.294
9/8/2005	North	N=>45 deg, 05 min	15.0	19.5	8.9	8.3	0.294
9/8/2005	North	N=>45 deg, 05 min	17.8	12.7	9.9	8.3	0.304
9/8/2005	North	N=>45 deg, 05 min	21.0	10.2	11.8	8.3	0.303
9/8/2005	North	N=>45 deg, 05 min	24.0	8.0	12.2	8.2	0.307
9/8/2005	North	N=>45 deg, 05 min	27.2	6.4	12.3	8.1	0.307
9/8/2005	North	N=>45 deg, 05 min	30.2	5.8	12.0	8.1	0.307
9/8/2005	North	N=>45 deg, 05 min	40.2	5.1	11.6	8.0	0.308
9/8/2005	North	N=>45 deg, 05 min	50.2	4.7	11.2	7.9	0.308
9/8/2005	North	N=>45 deg, 05 min	59.7	4.6	11.0	7.9	0.309
9/8/2005	North	N=>45 deg, 05 min	70.2	4.5	10.8	7.9	0.311

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
9/8/2005	South	S=>44 deg, 58 min	0.5	20.8	8.8	8.3	0.294
9/8/2005	South	S=>44 deg, 58 min	2.8	20.8	8.5	8.3	0.293
9/8/2005	South	S=>44 deg, 58 min	5.9	20.8	8.5	8.3	0.294
9/8/2005	South	S=>44 deg, 58 min	9.1	20.8	8.5	8.3	0.293
9/8/2005	South	S=>44 deg, 58 min	14.9	17.3	9.8	8.3	0.298
9/8/2005	South	S=>44 deg, 58 min	18.1	12.2	11.7	8.3	0.301
9/8/2005	South	S=>44 deg, 58 min	20.7	9.0	12.3	8.3	0.305
9/8/2005	South	S=>44 deg, 58 min	23.9	6.8	12.4	8.2	0.305
9/8/2005	South	S=>44 deg, 58 min	26.8	6.2	12.3	8.1	0.306
9/8/2005	South	S=>44 deg, 58 min	30.0	5.7	11.9	8.1	0.307
9/8/2005	South	S=>44 deg, 58 min	40.1	5.0	11.5	8.0	0.307
9/8/2005	South	S=>44 deg, 58 min	50.0	4.7	11.3	8.0	0.307
9/8/2005	South	S=>44 deg, 58 min	59.8	4.6	11.1	8.0	0.307
9/8/2005	South	S=>44 deg, 58 min	70.1	4.4	10.8	7.9	0.309
9/8/2005	South	S=>44 deg, 58 min	70.3	4.4	9.5	7.9	0.308
9/21/2005	North	N=>45 deg, 05 min	0.3	20.6	8.8	8.1	0.295
9/21/2005	North	N=>45 deg, 05 min	2.9	20.6	8.6	8.3	0.294
9/21/2005	North	N=>45 deg, 05 min	5.9	20.6	8.5	8.3	0.294
9/21/2005	North	N=>45 deg, 05 min	8.9	20.5	8.5	8.3	0.294
9/21/2005	North	N=>45 deg, 05 min	11.9	20.4	8.5	8.3	0.294
9/21/2005	North	N=>45 deg, 05 min	14.6	19.5	8.7	8.3	0.296
9/21/2005	North	N=>45 deg, 05 min	18.4	12.2	11.6	8.3	0.304
9/21/2005	North	N=>45 deg, 05 min	21.0	9.3	12.1	8.3	0.306
9/21/2005	North	N=>45 deg, 05 min	23.9	7.5	12.2	8.2	0.307
9/21/2005	North	N=>45 deg, 05 min	27.1	6.3	11.8	8.1	0.308
9/21/2005	North	N=>45 deg, 05 min	30.4	5.6	11.5	8.1	0.308
9/21/2005	North	N=>45 deg, 05 min	40.1	4.9	11.2	8.0	0.309
9/21/2005	North	N=>45 deg, 05 min	50.7	4.7	10.9	8.0	0.309
9/21/2005	North	N=>45 deg, 05 min	59.6	4.5	10.7	7.9	0.309
9/21/2005	North	N=>45 deg, 05 min	69.9	4.3	10.6	7.9	0.309
9/21/2005	North	N=>45 deg, 05 min	78.4	4.2	9.2	7.8	0.312
9/21/2005	South	S=>44 deg, 58 min	0.2	20.7	8.4	8.3	0.293
9/21/2005	South	S=>44 deg, 58 min	2.9	20.6	8.4	8.3	0.293
9/21/2005	South	S=>44 deg, 58 min	6.1	20.6	8.4	8.3	0.293
9/21/2005	South	S=>44 deg, 58 min	8.4	20.6	8.4	8.3	0.293
9/21/2005	South	S=>44 deg, 58 min	12.1	20.5	8.4	8.3	0.293
9/21/2005	South	S=>44 deg, 58 min	13.7	19.8	8.9	8.3	0.295
9/21/2005	South	S=>44 deg, 58 min	17.5	13.9	11.4	8.3	0.305
9/21/2005	South	S=>44 deg, 58 min	21.0	10.8	11.5	8.3	0.304
9/21/2005	South	S=>44 deg, 58 min	24.4	9.3	11.8	8.2	0.305
9/21/2005	South	S=>44 deg, 58 min	26.5	7.5	11.7	8.1	0.307
9/21/2005	South	S=>44 deg, 58 min	29.6	6.5	11.6	8.1	0.308
9/21/2005	South	S=>44 deg, 58 min	40.6	5.9	11.5	8.0	0.308
9/21/2005	South	S=>44 deg, 58 min	48.6	5.7	11.2	8.0	0.308
9/21/2005	South	S=>44 deg, 58 min	60.0	4.8	10.8	7.9	0.309
9/21/2005	South	S=>44 deg, 58 min	69.9	4.8	10.7	7.8	0.308

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
10/10/2005	North	N=>45 deg, 05 min	0.2	16.1	9.8	8.3	0.292
10/10/2005	North	N=>45 deg, 05 min	3.0	15.9	9.6	8.3	0.291
10/10/2005	North	N=>45 deg, 05 min	6.1	15.9	9.5	8.3	0.292
10/10/2005	North	N=>45 deg, 05 min	9.4	15.8	9.5	8.3	0.292
10/10/2005	North	N=>45 deg, 05 min	10.0	15.8	9.5	8.3	0.292
10/10/2005	North	N=>45 deg, 05 min	12.1	15.7	9.6	8.3	0.292
10/10/2005	North	N=>45 deg, 05 min	15.1	15.2	9.7	8.3	0.293
10/10/2005	North	N=>45 deg, 05 min	18.0	14.5	9.9	8.2	0.293
10/10/2005	North	N=>45 deg, 05 min	21.0	12.3	10.3	8.2	0.296
10/10/2005	North	N=>45 deg, 05 min	24.2	10.4	10.6	8.1	0.299
10/10/2005	North	N=>45 deg, 05 min	27.1	8.4	11.0	8.1	0.300
10/10/2005	North	N=>45 deg, 05 min	29.8	7.6	11.0	8.0	0.302
10/10/2005	North	N=>45 deg, 05 min	30.0	7.8	10.9	8.0	0.302
10/10/2005	North	N=>45 deg, 05 min	40.1	6.1	11.5	7.9	0.303
10/10/2005	North	N=>45 deg, 05 min	50.0	5.3	11.3	7.9	0.304
10/10/2005	North	N=>45 deg, 05 min	50.0	5.1	11.0	7.9	0.304
10/10/2005	North	N=>45 deg, 05 min	60.0	4.8	11.0	7.9	0.305
10/10/2005	North	N=>45 deg, 05 min	59.8	4.8	10.5	7.9	0.305
10/10/2005	South	S=>44 deg, 58 min	0.1	15.8	9.6	8.2	0.293
10/10/2005	South	S=>44 deg, 58 min	3.2	15.7	9.8	7.2	0.291
10/10/2005	South	S=>44 deg, 58 min	3.2	15.7	9.6	7.5	0.291
10/10/2005	South	S=>44 deg, 58 min	5.9	15.7	9.7	7.8	0.292
10/10/2005	South	S=>44 deg, 58 min	9.0	15.6	9.8	7.8	0.292
10/10/2005	South	S=>44 deg, 58 min	12.1	15.6	9.6	8.0	0.291
10/10/2005	South	S=>44 deg, 58 min	14.9	15.5	9.6	8.1	0.293
10/10/2005	South	S=>44 deg, 58 min	17.8	14.0	9.8	8.1	0.296
10/10/2005	South	S=>44 deg, 58 min	21.0	12.3	10.4	8.1	0.296
10/10/2005	South	S=>44 deg, 58 min	24.2	11.0	10.7	8.0	0.296
10/10/2005	South	S=>44 deg, 58 min	27.0	9.46	11.0	8.0	0.299
10/10/2005	South	S=>44 deg, 58 min	29.7	8.11	11.4	8.0	0.299
10/10/2005	South	S=>44 deg, 58 min	40.0	6.02	11.2	7.9	0.303
10/10/2005	South	S=>44 deg, 58 min	49.9	5.42	11.2	7.8	0.303
10/10/2005	South	S=>44 deg, 58 min	59.9	4.96	11.3	7.8	0.304
10/10/2005	South	S=>44 deg, 58 min	70.0	4.58	11.3	7.8	0.305
10/10/2005	South	S=>44 deg, 58 min	80.4	4.43	10.9	7.8	0.305
10/10/2005	South	S=>44 deg, 58 min	82.9	4.42	10.7	7.8	0.305
10/27/2005	North	N=>45 deg, 05 min	0.3	12.12	12.3	8.4	0.295
10/27/2005	North	N=>45 deg, 05 min	5.1	12.14	10.5	8.4	0.295
10/27/2005	North	N=>45 deg, 05 min	9.8	12.14	10.3	8.4	0.295
10/27/2005	North	N=>45 deg, 05 min	14.8	12.14	10.2	8.4	0.295
10/27/2005	North	N=>45 deg, 05 min	20.0	12.01	10.2	8.4	0.295
10/27/2005	North	N=>45 deg, 05 min	24.7	11.05	10.4	8.3	0.297
10/27/2005	North	N=>45 deg, 05 min	28.9	10.27	10.7	8.3	0.299
10/27/2005	North	N=>45 deg, 05 min	35.0	8.16	11.0	8.2	0.301
10/27/2005	North	N=>45 deg, 05 min	43.2	6.56	10.9	8.1	0.303
10/27/2005	North	N=>45 deg, 05 min	50.9	5.96	11.0	8.1	0.303
10/27/2005	North	N=>45 deg, 05 min	59.6	5.46	10.8	8.0	0.304
10/27/2005	North	N=>45 deg, 05 min	72.2	5.13	10.9	8.0	0.305

Date MM/DD/YYYY	Location	GPS	Depth (m)	T (C)	DO (mg/l)	pH	Sp. Cond. (mS/cm)
10/27/2005	South	S=>44 deg, 58 min	0.3	12.45	10.8	8.3	0.294
10/27/2005	South	S=>44 deg, 58 min	5.2	12.48	10.4	8.3	0.294
10/27/2005	South	S=>44 deg, 58 min	9.8	12.48	10.3	8.3	0.293
10/27/2005	South	S=>44 deg, 58 min	14.4	12.47	10.3	8.3	0.294
10/27/2005	South	S=>44 deg, 58 min	19.3	12.47	10.2	8.3	0.293
10/27/2005	South	S=>44 deg, 58 min	25.0	11.77	10.2	8.3	0.295
10/27/2005	South	S=>44 deg, 58 min	30.0	7.55	11.3	8.1	0.301
10/27/2005	South	S=>44 deg, 58 min	35.1	6.79	11.3	8.1	0.302
10/27/2005	South	S=>44 deg, 58 min	39.8	6.13	11.4	8.0	0.302
10/27/2005	South	S=>44 deg, 58 min	48.1	5.74	11.0	8.0	0.303
10/27/2005	South	S=>44 deg, 58 min	60.1	5.19	11.0	8.0	0.303
10/27/2005	South	S=>44 deg, 58 min	69.3	4.89	11.1	7.9	0.304
10/27/2005	South	S=>44 deg, 58 min	79.7	4.62	10.7	7.9	0.303

Appendix III

Analysis of Sediment Phosphorus Release and Other Sediment Characteristics in Torch Lake, Clam Lake, and Lake Bellaire

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Prepared for

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September 1, 2005

Study Objectives:

The goal of this study was to characterize the sediments in Torch Lake, Clam Lake, and Lake Bellaire and to determine the magnitude of internal phosphorus-release and sediment oxygen demand (SOD). Our first objective was to describe the sediments in Torch Lake, Clam Lake, and Lake Bellaire and to accurately compare sediment in these lakes to sediment in other Michigan lakes. Sediment characteristics of interest included % water, % organic matter, total sediment phosphorus (mg/g dry), grain size (% sand/% silt /% clay) and sediment oxygen demand (g O^2/m^2/day). Our second objective was to examine the effect of hypolimnetic oxygen concentration on sediment phosphorus release. Sediment oxygen demand (SOD) along with other sediment parameters should provide a better understanding of the sediment processes influencing oxic/anoxic phosphorus release.

Methods:

Sediment cores along with sediment grab samples were collected from Clam Lake and Lake Bellaire on 25 May 2005. Sediment grab samples were also collected from two locations in Torch Lake on 25 May 2005, and sediment cores were collected from the same approximate locations on 1 June 2005. Sediment cores and grab samples were immediately transported on ice to the aquatic ecology laboratory at Central Michigan University for incubation and analysis. Sediment cores were collected with a modified Kajak-Brinkhurst corer to measure phosphorus-release and SOD in the overlying water, and grab samples were collected with a mini-Ponar grab sampler to establish general sediment characteristics. Three sediment cores and one grab sample were each collected from the deepest location of Lake Bellaire, Clam Lake, and Torch Lake. An additional site of intermediate depth was chosen in Torch Lake, and two sediment cores and one grab sample were collected for analysis. In addition, lake water was collected on the day of sampling with a Van Dorn sampler and later filtered through a 0.45 μm Millipore filter. The filtered lake water (FLW) was used for oxic/anoxic phosphorus-release blanks, a SOD blank, and for replacement water in the phosphorus-release sediment cores.

Grain size, % organic matter, and total sediment phosphorus (TP) were all determined from sediment grab samples. Sediment dry weight was determined with standard methods in triplicate by calculating the difference between initial wet weight and final dried weight after drying for at least 24 hours at ~105°C. Determination of sediment grain size was conducted using the hydrometer method (Bouyoucos' method) on previously dried sediment. Percent sand (2.0-0.05 mm), percent silt (0.05-0.002 mm), and percent clay (<0.002 mm) were established according to Stoke's Law, which is based on the known settling velocity of the different size fractions. Percent organic matter was determined according to standard methods by heating to ~550°C for a minimum of 2 hours and then weighing each crucible to calculate the percent decrease in sediment dried weight. TP analysis was conducted in triplicate using 100-125 mg of dried, homogenized sediment re-hydrated with 50 ml of deionized water. Eluted phosphorus concentrations were analyzed using the molybdenum blue/ascorbic acid method and a Beckman spectrophotometer (American Public Health Association *et al.* 1998).

All sediment cores were incubated in a walk-in cooler in the dark at 7.5°C ±2°C for the duration of the experiment. The technique of SOD determination was modeled after Gardiner's (1984) oxygen demand experiments. In the SOD cores, compressed air was bubbled into the overlying water for approximately two hours before monitoring to saturate the overlying water with oxygen. After the cessation of bubbling, dissolved oxygen was measured in 15-minute intervals using a Hydrolab Mini-Sonde 4a permanently inserted through the top of the core and connected to a Hydrolab Surveyor 4a data logger. While dissolved oxygen was logged, the stirring mechanism on the mini-sonde mixed the overlying water inside each core and prevented the development of an oxycline. Dissolved oxygen in each core was monitored for at least 8 hours, so the slope of the best fit line corresponding to the linear dissolved oxygen depletion rate could be observed. SOD was determined from the decrease over time in dissolved oxygen (mg O^2/L) in the overlying water. The dissolved oxygen depletion rate in each core was converted to a SOD rate (mg O^2/m^2/day) based on the volume of overlying water and the sediment surface area. One additional core was filled only with FLW and served as a control. The blank indicated the dissolved oxygen depletion rate that existed in cores containing no sediment. The slope of the best fit line describing dissolved oxygen depletion in the blank core was also determined and was used to correct the observed SOD rates in each sediment core, so that only the sediment was considered in the final SOD rates.

The phosphorus release experiments were handled similarly to studies done by Kamp-Nielson (1974) and Penn *et al.* (2000) in which p-release was monitored under both oxic and anoxic conditions. The phosphorus-release cores were exposed to either oxic or anoxic treatments to mimic the seasonal dissolved oxygen extremes that naturally occur in the hypolimnion of some lakes. Separate cores from each site were monitored under oxic/anoxic conditions. For the length of each phosphorus release experiment, oxic conditions were achieved by continuously bubbling compressed air into the overlying water, and anoxic conditions were simulated by bubbling nitrogen into the overlying water (Penn *et al.* 2000). Phosphorus-release was calculated as the increase in total dissolved phosphorus (TDP) over time in the overlying water (Ignatieva 1996). TDP was measured to avoid including any suspended particulate-bound phosphorus. TDP-release was converted to μg P/m^2/day based on the volume of overlying water and sediment surface area. TDP-release into the overlying water was determined from 50 ml samples collected every second day. The sample volume extracted from each core was then immediately replaced with FLW. TDP concentrations were identically determined for replacement FLW at the same time intervals and used to determine the corrected TDP concentration in each core after every FLW addition. Thus, the TDP-release rates for each core were determined from the slope of the cumulative increase in TDP over the sampling intervals. Since sediment cores were collected from Torch Lake at a later date, only 4-day TDP-release rates could be determined. Therefore, only 4-day oxic/anoxic TDP-release rates were directly compared between lakes. One blank core for each treatment was also monitored to assess any change in TDP concentration not associated with the sediments that may have occurred during the incubation period or sampling process. The TDP-release rates for the blank cores were also included in the summary data, but unlike the final SOD rates the blanks were not factored into the final TDP-release rates reported for the sediment cores.

Sediment Data Summary:

Table 1: Sediment Grab Sample Data

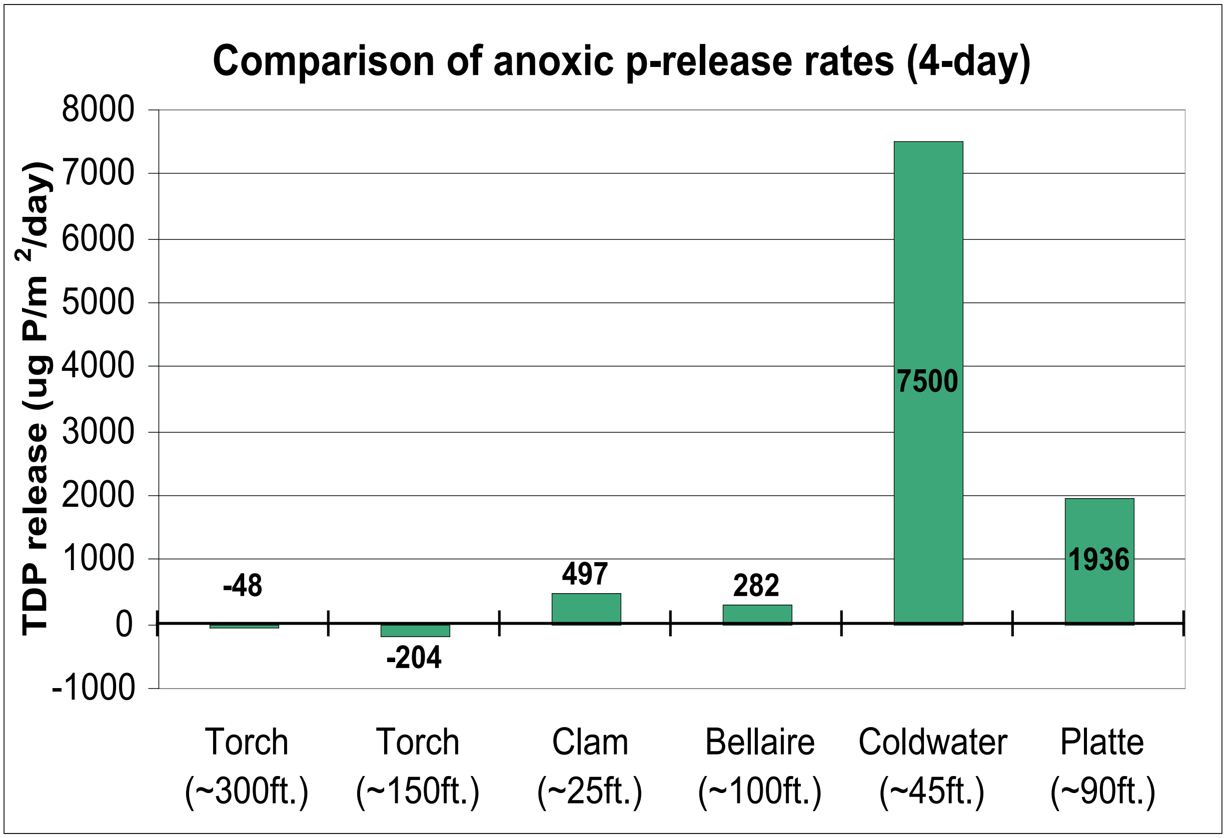
Site-Depth	Sediment TP (mg/g)	% Organic matter	% Sand (2.0-0.05 mm)	% Silt (0.05-0.002 mm)	% Clay (<0.002 mm)
Torch (~300ft.)	0.238*	7.83%	27.3	21.1	51.6
Torch (~150ft.)	0.140	4.61%	32.5	28.1	39.4
Clam (~25ft.)	0.187	19.19%	59.7	28.0	12.3
Bellaire (~100ft.)	0.189	16.87%	54.8	30.1	15.1

**Sediment TP ranging from 0.274-0.307 mg/g were established in previous sediment samples taken from the top 0-25 cm of sediment (Analyzed on 12/23/04 by the Great Lakes Environmental Center, Traverse City, MI)*

Table 2: Sediment Core Data

Site-Depth	***4-day*** **Oxic TDP release (_g P/ m²/day)**	***10-day*** **Oxic TDP release (_g P/ m²/day)**	***4-day*** **Anoxic TDP release (_g P/ m²/day)**	***10-day*** **Anoxic TDP release (_g P/ m²/day)**	**SOD (g O²/ m²/day)**
Torch (~300ft.)	129	---	-48	---	0.36
Torch (~150ft.)	---	---	-204	---	0.17
Clam (~25ft.)	137	203	497	387	1.08
Bellaire (~100ft.)	-9	298	282	320	0.54
Blank	323	262	426	357	---

Figure 1: Anoxic and oxic phosphorus release rates in Torch Lake, Clam Lake and Lake Bellaire (Antrim Co.) relative to rates in Platte Lake (Benzie Co.) and Coldwater Lake (Isabella Co.).



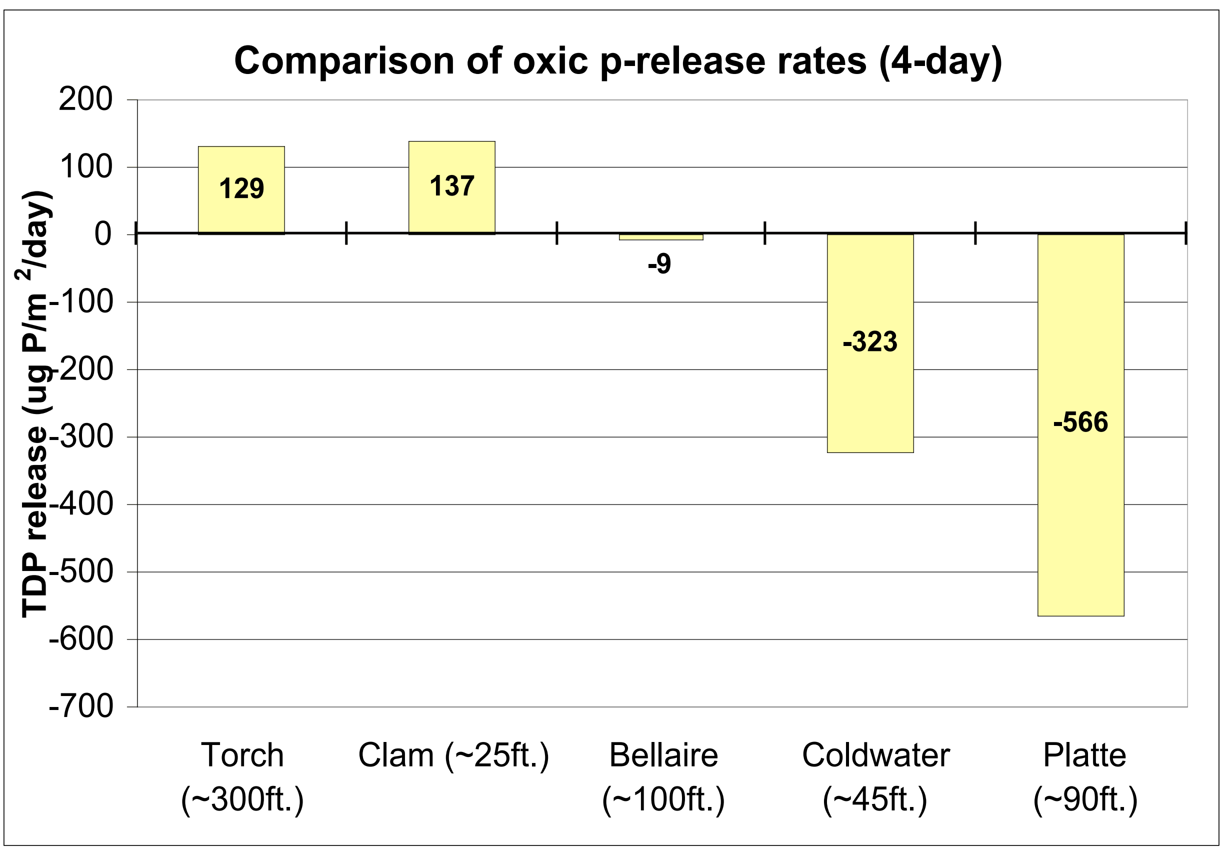
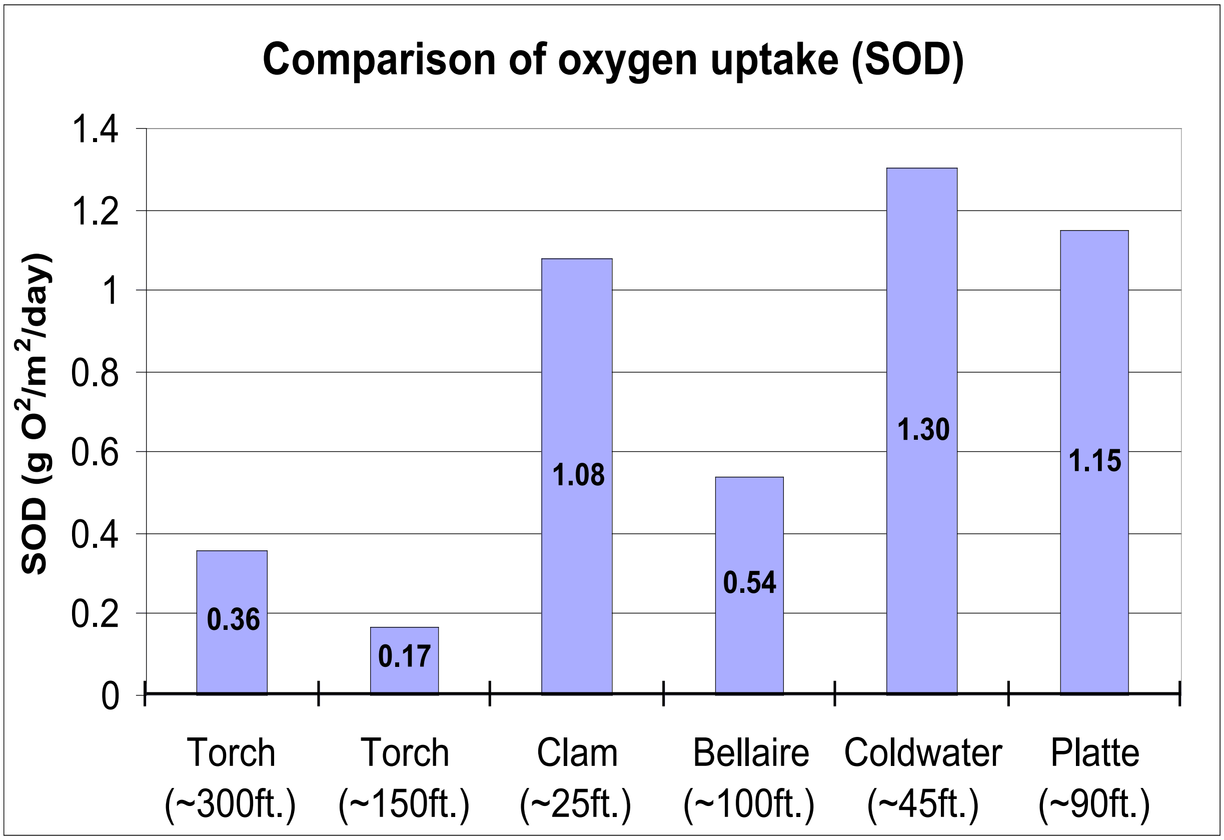


Figure 2: SOD and TP concentration in sediment from Torch Lake, Clam Lake and Lake Bellaire (Antrim Co.); Platte Lake (Benzie Co.); and Coldwater Lake (Isabella Co.).



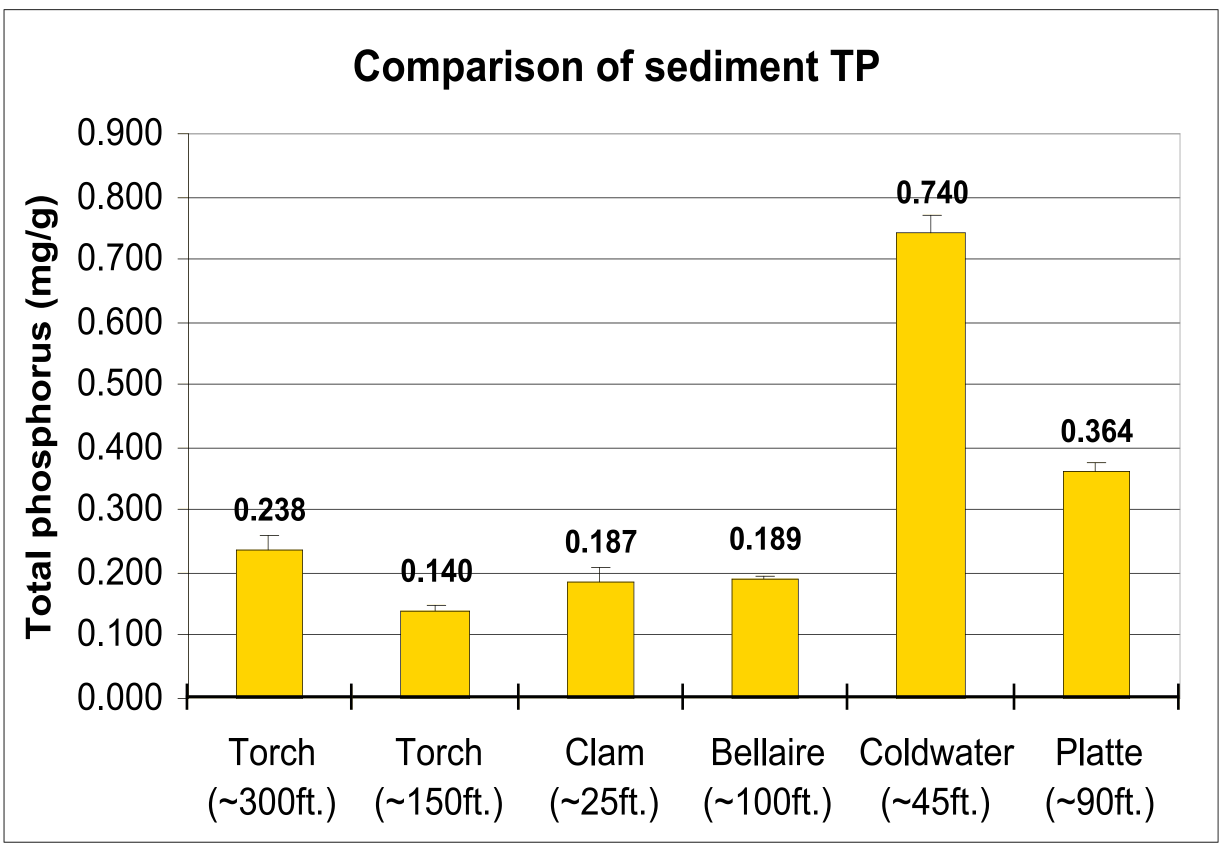
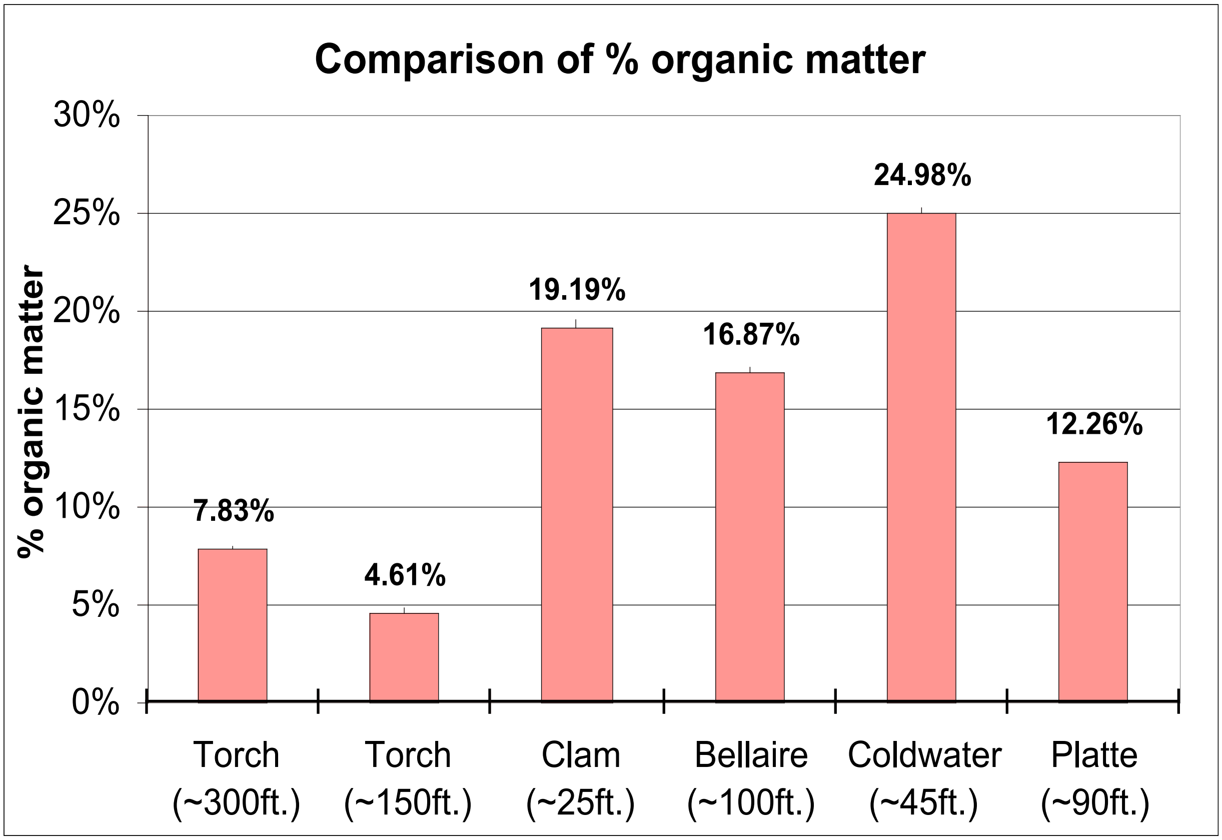
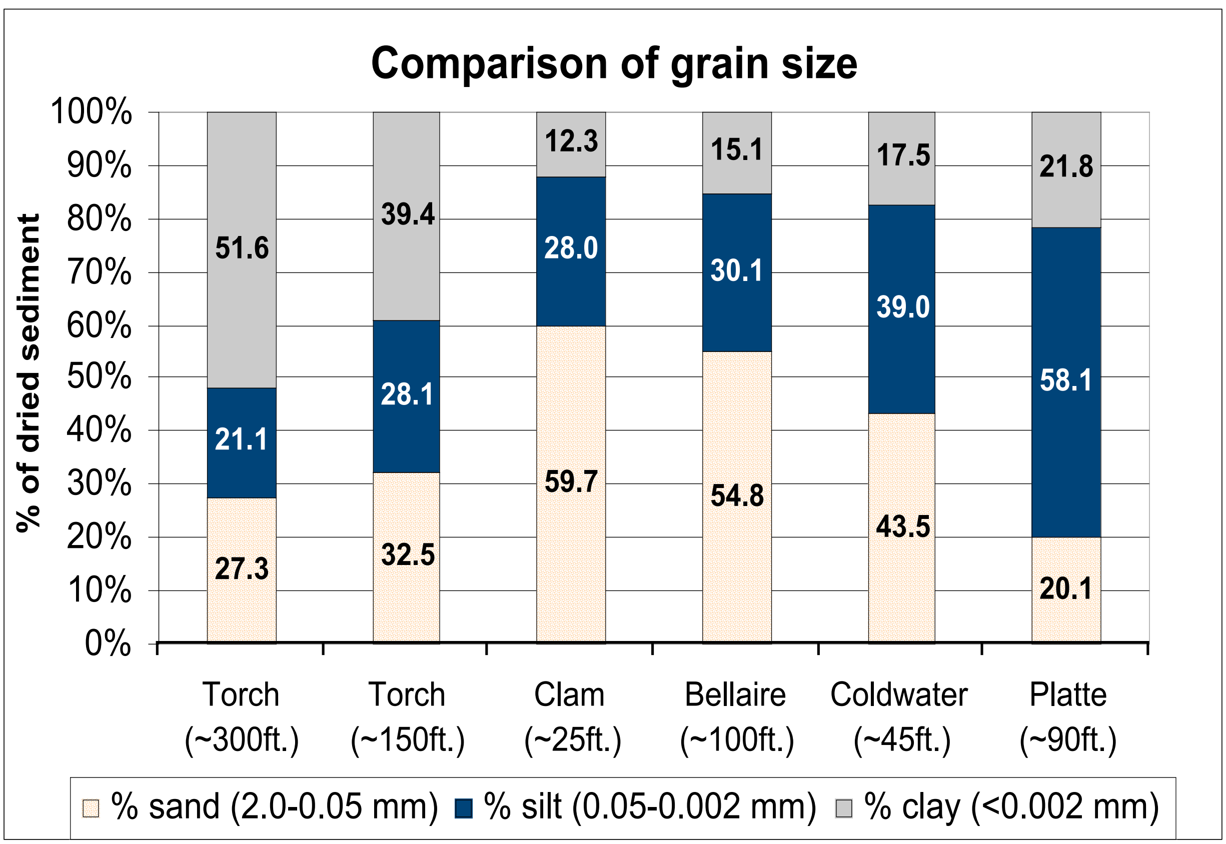


Figure 3: Percent organic matter and grain size of sediment from Torch Lake, Clam Lake and Lake Bellaire (Antrim Co.); Platte Lake (Benzie Co.); and Coldwater Lake (Isabella Co.).





Results and Discussion:

Torch Lake sediment was low in total phosphorus and % organic matter but contained a high percentage of clay (*Table 1*). Both locations in Torch Lake had low % organic matter with the shallower of the two locations showing the lowest percentage. The low % organic matter in Torch Lake corresponded to high % clay, with the deepest location in Torch Lake showing distinctly greater clay content than any other location (*Figure 3*). Sediment from Clam Lake and Lake Bellaire was also characterized by a low TP content. However, sediment from these lakes was high in organic matter and contained a large percentage of sand (*Table 1*).

In comparison to more productive lakes like Coldwater Lake (Isabella Co.) and Platte Lake (Benzie Co.), sediment in Torch Lake, Clam Lake, and Lake Bellaire was very low in TP and % silt (*Figures 2, 3*). The deepest location in Torch Lake yielded the highest TP of the 3 lakes (*Table 1*), but this was negligible compared to that in Coldwater Lake. TP determined for the deepest location in Torch Lake in this study was similar to previous TP values for the deepest location in Torch Lake that were assessed in 2004 (*Table 1*). The difference in TP between the two locations in Torch Lake is consistent with the general trend of decreasing TP with decreasing water depth, which is typical of most deep lakes. The % organic matter in sediment from Clam Lake and Lake Bellaire was comparable to that from Coldwater Lake and Platte Lake (*Figure 3*).

Overall, TDP-release rates from Torch Lake, Clam Lake, and Lake Bellaire sediment cores were negligible (< 500 μg P/m^2/d; *Table 2*). Coldwater Lake and Platte Lake showed noticeably greater, positive anoxic TDP-release and lower, negative oxic TDP- release (*Figure 1*). The grab sample data were used to elucidate potential factors influencing p-release and SOD. For instance, the higher TDP-release rates for Platte Lake and Coldwater Lake appear to be partially explained by a high percentage of silt containing high TP and a large amount of easily degraded organic matter (*Figures 2, 3*). For Torch Lake, the high clay and low organic matter content coupled with a relatively high TP content (compared to Clam and Bellaire) seem to indicate a potential for considerable phosphorus adsorption to clay complexes, which could explain the low TDP-release rates. It appears that redox conditions and associated compounds, such as iron and manganese hydroxides, do not significantly regulate the mobility of sediment phosphorus in Torch Lake, since oxic TDP-release was positive and anoxic TDP-release was negative (*Table 2*). Negative anoxic TDP-release (TDP uptake) may be a sign of suppression of aerobic bacteria, which would normally break down organic matter and release phosphorus. Positive oxic TDP-release may result from undeterred aerobic microbial processes.

Phosphorus exchange (release/uptake) was lower than expected in both Clam Lake and Lake Bellaire based solely on the high % organic matter of the sediments (*Tables 1, 2*). It seems to indicate that much of the organic matter in Clam Lake and Lake Bellaire is not easily broken down. Some sediments containing a high percentage of certain organic compounds, such as lignin, decompose incompletely and exchange less phosphorus with the overlying water. Furthermore, Clam Lake yielded positive TDP-release under both oxic and anoxic conditions (*Table 2*). Lake Bellaire showed a more typical pattern of positive TDP-release under anoxic condition and of negative TDP-release under oxic conditions (*Table 2*). It should also be noted that the formation of visible iron complexes during oxic conditions was not apparent in any cores from Torch Lake, Clam Lake, or Lake Bellaire. The presence of these oxidized iron compounds was evident in sediments from Platte Lake and Coldwater Lake, often forming a rust-colored oxidized microlayer at the sediment surface in oxic cores, and coincided with high anoxic TDP-release rates. It has been well documented that under oxic conditions this microlayer binds phosphorus and that under anoxic conditions phosphorus is released during dissolution of reduced compounds (Penn *et al.* 2000).

However, it should be stressed that in each sediment core from Torch Lake, Clam Lake, and Lake Bellaire, the increase or decrease in TDP between sampling intervals was not substantial enough to yield strong evidence supporting either TDP-release or TDP-uptake during test conditions (*Appendix*). The TDP-release rates calculated for both oxic and anoxic blanks were similar to the rates calculated for cores with sediment. The measured TDP concentrations for these sediment cores were much lower (TDP concentrations never exceeded 13 μg/L) than in sediment cores from more productive lakes (TDP concentrations exceeded 300 μg/L in the Coldwater Lake anoxic core). In TDP-release experiments for more productive lakes, much more gradual slopes, which correspond to low TDP-release/TDP-uptake rates, were found in the blank cores than in sediment cores due to less increase/decrease in TDP concentration during the duration of the experiment. Thus, there seems to be little exchange of dissolved phosphorus compounds between the sediment and the overlying water in Torch Lake, Clam Lake, and Lake Bellaire when compared to more eutrophic lakes.

SOD rates were also low, with the exception of Clam Lake, in comparison to Platte Lake and Coldwater Lake (*Figure 2*). The high SOD rate for Clam Lake coincided with high organic matter content, which was surprisingly not the case in Lake Bellaire as the relatively high % organic matter corresponded to a comparatively low SOD rate (*Tables 1, 2*). The low SOD rate for Lake Bellaire seems to support the likelihood of a high percentage of refractory organic matter, which would result in slow decomposition, further resulting in a low SOD rate (*Table 2*). Moreover, a general increase in dissolved oxygen with depth in Clam Lake was collected with the Hydrolab on the day of sampling (*Appendix*). The high *in situ* dissolved oxygen was probably related to the occurrence of small macrophytes on the sediment surface, which were observed in the sediment cores. Since SOD rates were determined in the dark, the high SOD rate observed may be misleading since the replenishment of dissolved O_2 in the overlying water from photosynthesis was probably reduced and O_2 consumption by macrophytic respiration may have concurrently increased. Nonetheless, with the high O_2 present above the sediment-water interface evident from Hydrolab profile, it would seem that the SOD would likely not cause prolonged anoxia in the overlying water under natural conditions. Therefore, even though the SOD rate observed in Clam Lake is similar to those rates of more productive lakes, the shallow water depth and the presence of macrophytes may counteract the effect of the high SOD rate on the water overlying the sediment in Clam Lake during the warmer months. However, the reduction of lake mixing and of O_2 release from macrophytes, as may occur during heavy ice and snow cover on the water surface, could allow the sediments to have a more pronounced effect on O_2 concentration in the overlying water.

Moreover, sediment TP, % organic matter, and grain size for both Clam Lake and Lake Bellaire were very similar (*Table 1*). Yet, somewhat surprisingly, SOD and anoxic TDP-release for Lake Bellaire was roughly half that of Clam Lake, although the TDP-release still is low especially considering the blanks (*Table 2; Appendix*). The high organic matter and % sand content collectively with low TP indicates that the highly organic sediment is mainly composed of large particulates with mostly refractory forms of phosphorus. However, further degradation of these highly organic sediments may yield increased future TDP-release. The role of macrophytes in regulation of TDP-release in Clam Lake is also not known. Even though Clam Lake and Lake Bellaire had much greater % organic matter than Torch Lake, sediment TP was nearly equivalent in the 3 lakes (*Table 1*). Thus, sediment phosphorus appears to be present in different prevailing forms in the 3 lakes. In Torch Lake, the low % organic matter, high % clay, and low TDP-release rates relative to TP point toward the dominance of p-sorption to clay complexes. Since the determination of sediment TP was conducted using the ascorbic acid method, the values presented for sediment TP likely included phosphorus compounds adsorbed onto clay complexes but may have excluded some refractory phosphorus compounds bound to larger organic particulates, therefore explaining the similarity of TP values in all 3 lakes. The use of another digestion procedure with a stronger acid may have resulted in higher reported TP concentrations in Clam Lake and Lake Bellaire.

Literature Cited:

American Public Health Association et al. 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition. American Public Health Association. Washington, D.C. p. 4-139-4-144.

Gardiner, R.D. 1984. Sediment oxygen demand and related surficial sediment characteristics in Green Bay (Lake Michigan). Master's Thesis, Department of Civil Engineering, Michigan Technological University, Houghton, Michigan.

Ignatieva, N.V. 1996. Distribution and release of sedimentary phosphorus in Lake Ladoga. *Hydrobiologia*. 322: 129-136.

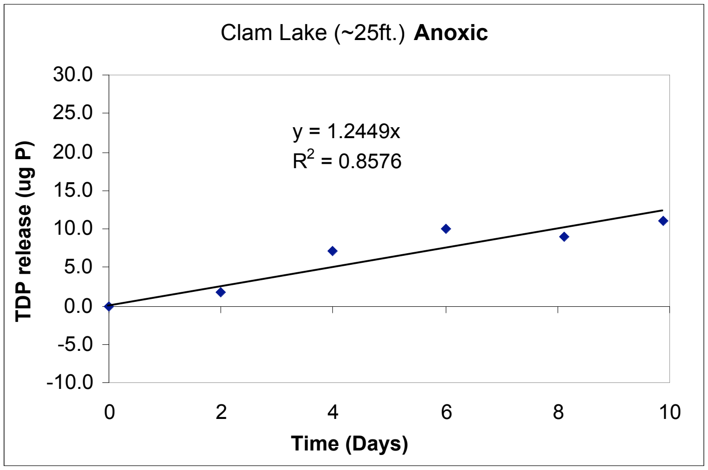
Kamp-Nielson, L. 1974. Mud-water exchange of phosphate and other ions in undisturbed sediment cores and factors affecting the exchange rates. *Archiv fur Hydrobiologie*. 73: 218-237.

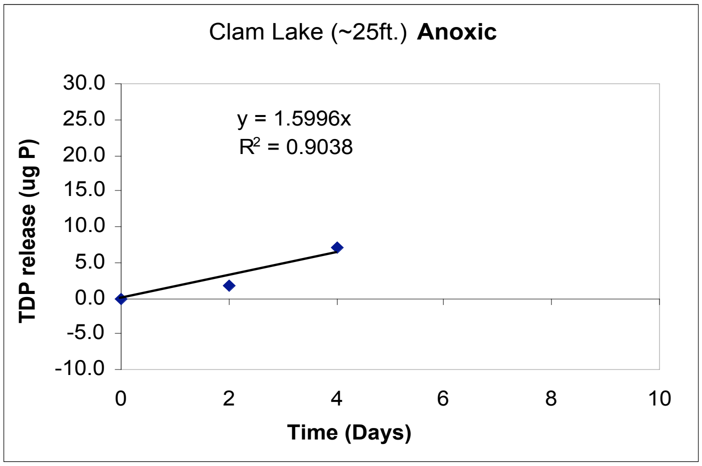
Penn, M.R., Auer, M.T., Doerr, S.M., Driscoll, C.T., Brooks, C.M., and Effler, S.W. 2000. Seasonality in phosphorus release rates from the sediments of a hypereutrophic lake under a matrix of pH and redox conditions. *Canadian Journal of Fisheries and Aquatic Sciences*. 57: 1033-1041.

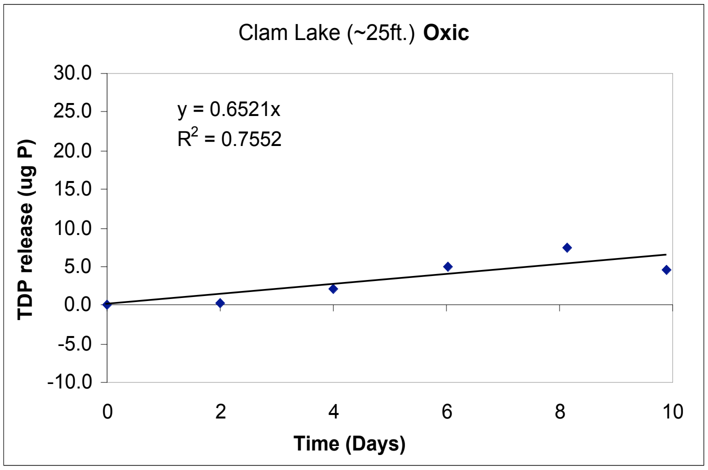
Appendix

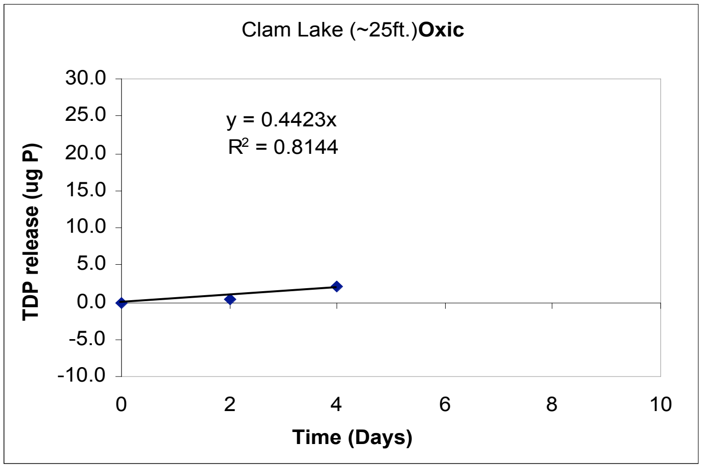
Clam Lake P-release plots:

*10-day rate is left plot; 4-day rate is right plot (**Both rates are from the same core)*



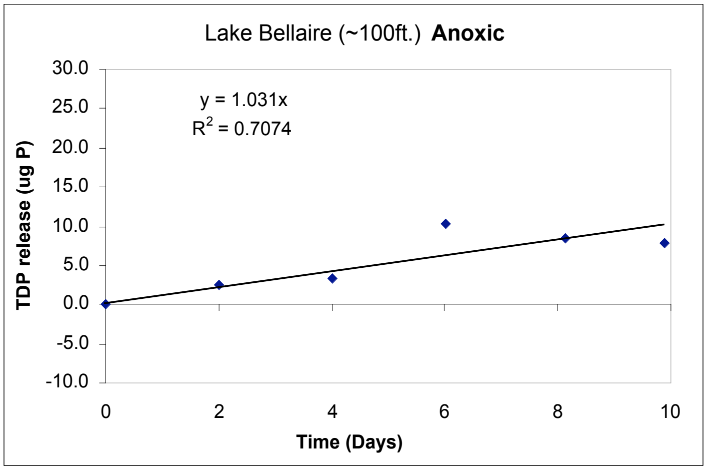


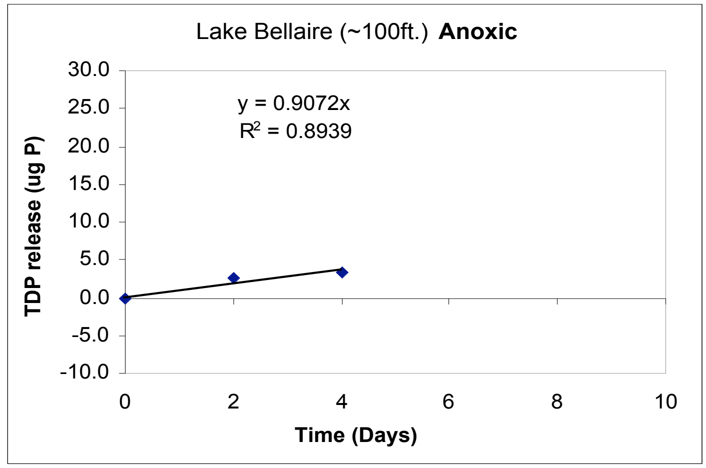


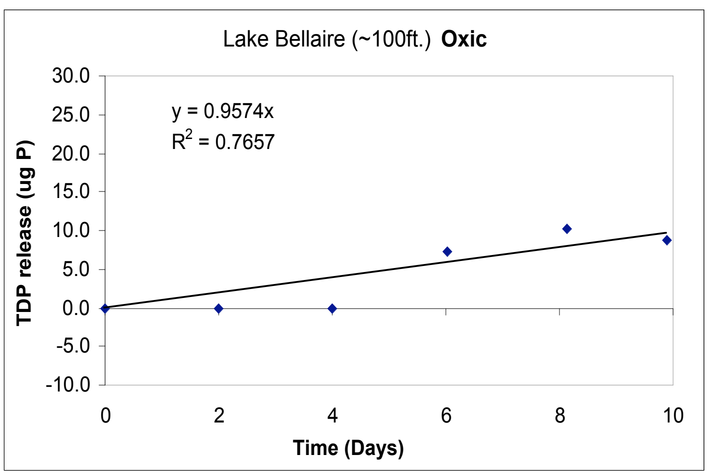


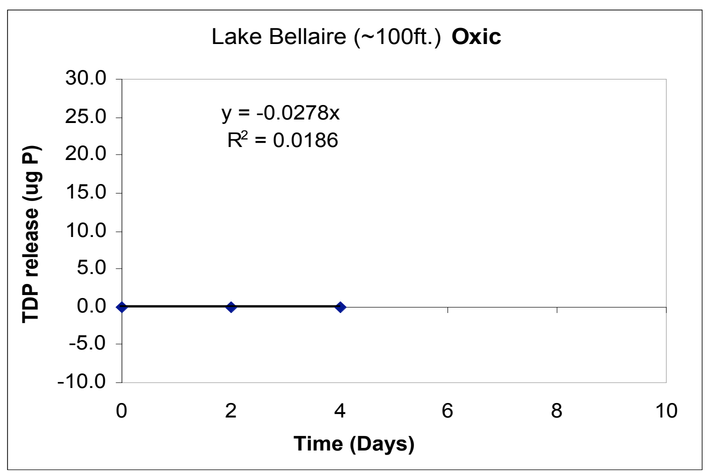
Lake Bellaire P-release plots:

*10-day rate is left plot; 4-day rate is right plot (**Both rates are from the same core)*

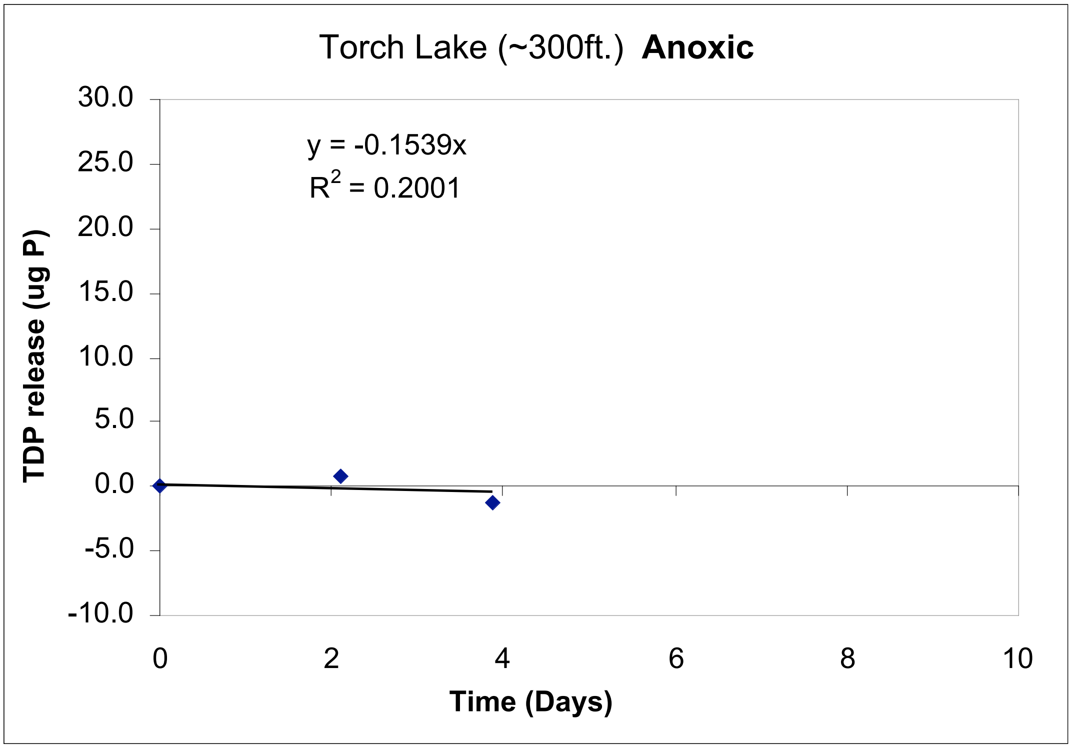


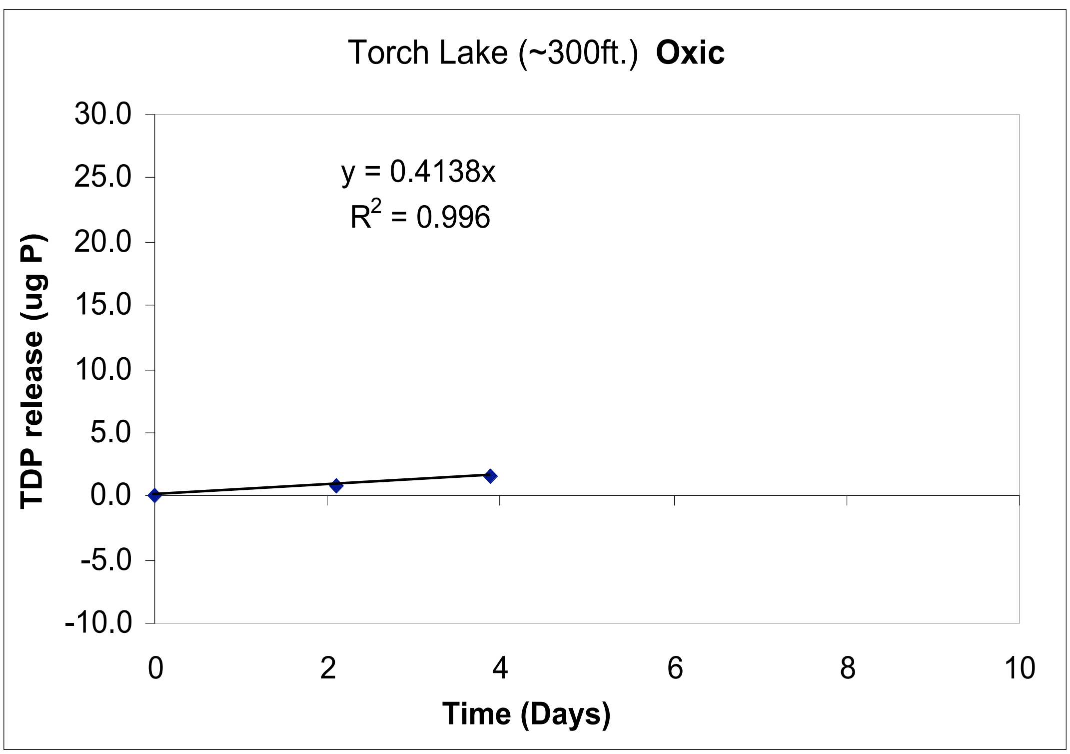




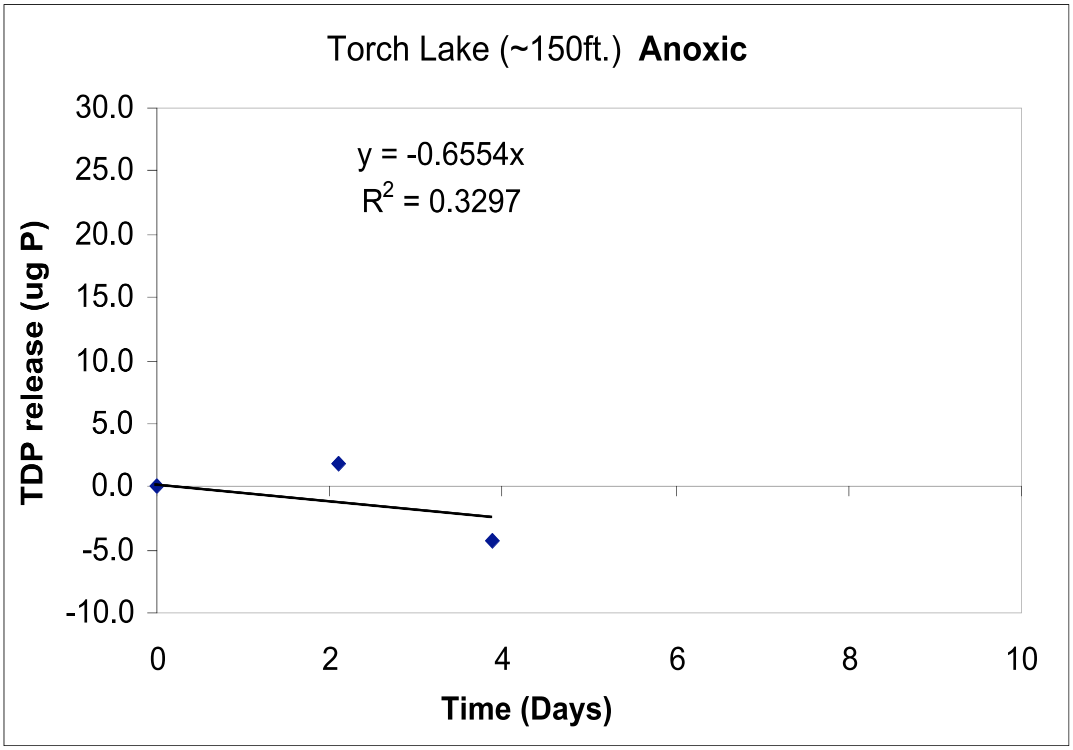


Torch Lake (~300 ft.) P-release plots:



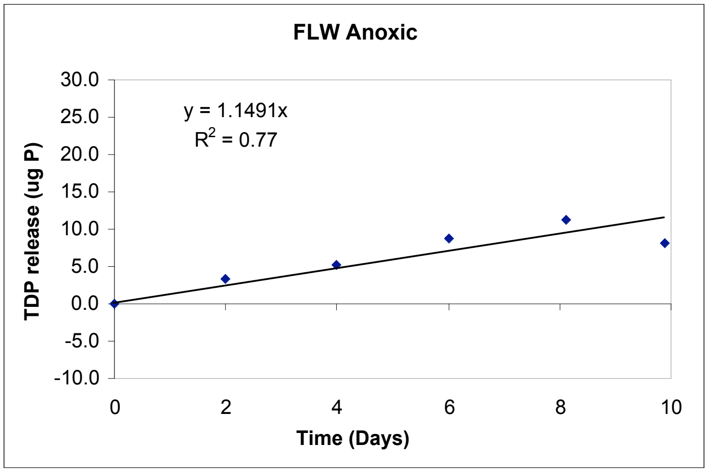


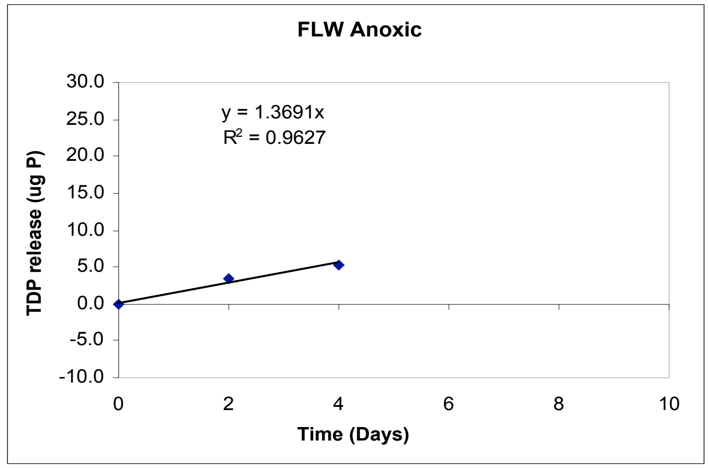
Torch Lake (~150 ft.) P-release plot:

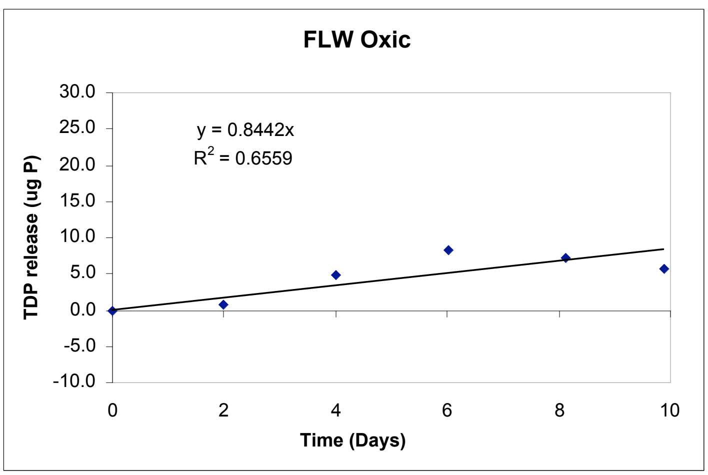


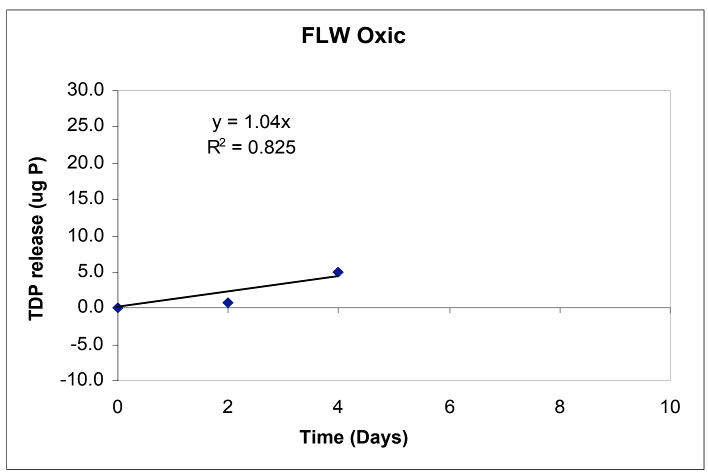
Anoxic and Oxic P-release Blanks (No Sediment):

*10-day rate is left plot; 4-day rate is right plot (**Both rates are from the same core)*









Hydrolab vertical profiles from 25 May 2005: