MEASURING THE TROPHIC STATUS OF LAKES SAMPLING PROTOCOLS

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MEASURING THE TROPHIC STATUS OF LAKES
SAMPLING PROTOCOLS

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Summary

Studies conducted at the Dorset Research Centre have resulted in long-term records of phosphorus, chlorophyll a, Secchi depth, and oxygen in lakes. These are the measures most commonly used to estimate the trophic status of lakes. Analysis of these long-term data series are presented with a practical view for setting up sampling programs for the determination of the trophic status of a lake. Depending on the accuracy desired, the minimum number of samples required to produce a good estimate of each of several trophic status measures are presented. Sample collection techniques are reviewed and cautions noted about the collection of samples, and the submission of samples to the laboratory.

Consideration is also given to the collection of data for use with current models such as the Trophic Status Model (Lakeshore Capacity Study), in addition to oxygen and chlorophyll models.

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Introduction: Measuring the Trophic Status of Lakes

The trophic status of a lake is determined by the levels of plant nutrients in the water. In most north-temperate lakes, phosphorus is the element which controls the growth of primary producers (algae). For this reason, phosphorus is considered as the key trophic status indicator. The only meaningful measurement of phosphorus in lake water under normal conditions is total phosphorus. However, the total phosphorus concentration of lake water is not constant, so it is not possible to report a phosphorus value without qualifying it. Commonly used estimates of phosphorus in lake water include spring turnover concentrations, whole lake ice-free means, and stratified season 'epilimnetic' averages. With proper attention to sampling regime and analytical protocol, reliable estimates of all of these can be made. Soluble reactive phosphorus (SRP), usually interpreted as a measure of orthophosphate (PO_4), has also been measured widely. It is recognized that PO_4 is the biologically active form of phosphorus, but the turnover rate of PO_4 in phosphorus-limited conditions is extremely rapid. Not only does the conventional molybdate test overestimate biologically available PO_4 by one or two orders of magnitude (Rigler 1966), but it has recently been shown that filtration techniques commonly used in the analysis of PO_4 results in a further overestimate of biologically active phosphorus (Fisher and Lean 1992). For practical purposes, the routine measurement of SRP as a trophic status indicator is meaningless.

Phosphorus is necessary for algae growth, and the production of algae most noticeably affects the aesthetic quality and 'visual' trophic status of the lake. Chlorophyll a is the parameter most often used to quantify the biomass of primary producers in the water and as a result chlorophyll a levels are often used as indicators of trophic status. Algal biomass or algal enumeration are often quoted in relation to trophic status but are more time consuming and expensive to collect.

Since algal density has a major effect on water clarity, there is a relationship between water clarity (Secchi depth) and algal biomass in many lakes. Consequently, Secchi depths have commonly been used as approximations of trophic status. The advantages of Secchi depth is that it is simple and inexpensive to obtain, and historical records do not suffer from changes in methodology.

When the lake supports a community of cold water fish, oxygen concentrations are often critically important. Lake morphometry has been shown to be the most influential parameter for predicting hypolimnetic oxygen concentrations in oligotrophic lakes (Molot *et. al.* 1992), but the oxygen regime is also modified by changes in the lake's phosphorus concentration.

As a result, oxygen profiles are often considered as a consequence of the trophic status of the lake, and are important as a direct measure of vital habitat for some species of fish.

As with phosphorus, all of the above measures of the trophic status of a lake undergo seasonal and annual variation. Much of this variation is due to the annual cycle of growth and biological production in the lake, and to the thermal stratification of most deeper lakes. Single number estimates of trophic status from any of these parameters require qualification to identify how the estimate was derived.

Monitoring long term changes in trophic status requires the collection of data that accounts for temporal or spatial variations in the parameter of interest. In addition, trophic status models are commonly used to estimate present day TP concentrations in a lake and to predict changes in trophic status resulting from human activities (Dillon and Rigler 1975, Chapra and Canale 1991, Reckhow and Simpson 1980, Canfield and Bachmann 1981). Careful attention must be paid to the collection of trophic status data for comparison with output from such models or for use as model input. A common error is the comparison of a single spring overturn phosphorus concentration with the output of a model which predicts the long-term ice-free mean. These types of comparison can be misleading or meaningless.

This report uses the long-term records of total phosphorus, chlorophyll, oxygen and Secchi disc data generated by studies at the Dorset Research Centre for a number of central Ontario lakes , and uses those data to develop optimal sampling strategies.

Methods

Phosphorus, chlorophyll, oxygen concentration and Secchi disc depth data have been collected at the Dorset Research Centre for many lakes since 1976. These lakes are described in Dillon *et. al.* (1986). The methods used to collect the samples are described in Locke and Scott, (1986). Chemical analyses were performed according to methods described in MOE (1985).

Throughout the following report, sample frequency recommendations are made for varying degrees of accuracy based on equations outlined in Green (1979). The formulae used to derive these recommendations are outlined in Appendix 5.

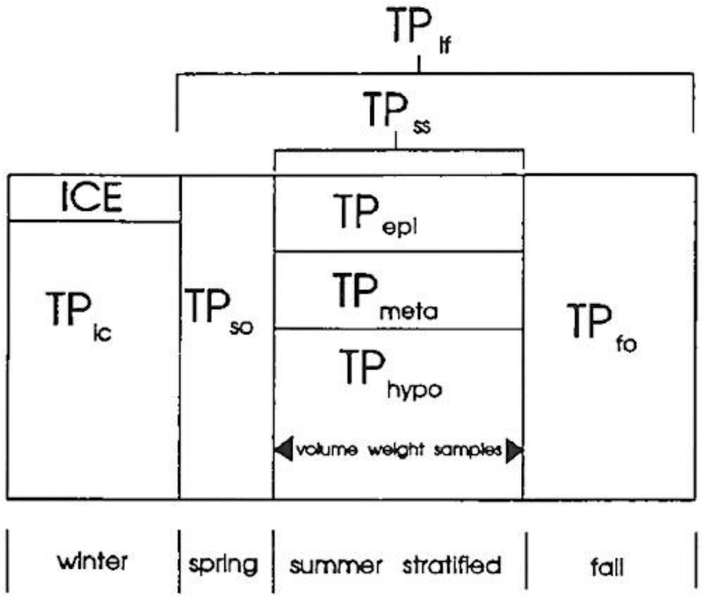

Figure 1: Seasons and depths of commonly used TP measurements. (ic=ice cover, so=spring overturn, if=ice free, ss=summer stratified, epi= epilimnetic, meta=metalimnetic, hypo= hypo-limnetic, fo= fall overturn).

Estimating Total Phosphorus

Total phosphorus (TP) can be measured and reported in many different ways. TP values may be based on the results of a single measurement taken at spring turnover, as an average of several observations made on a seasonal basis, as an estimate of a specific lake stratum, or as a whole lake approximation (Dillon *et al.* 1986). Figure 1 shows several of the common seasonal and lake stratum combinations that are used in reporting phosphorus concentrations. Many lake models predict or require a specific estimate of TP as one of their terms. The two most common measurements are either spring turnover (TP_{so}) or ice-free mean (TP_{if}). Spring overturn estimates are generally based on the results from a single spring sample while ice free estimates are derived as the average of several samples taken over the course of the ice free season. Ice free averages which encompass a period of stratification in the lake require the collection of volume weighted samples during the stratification in order to derive proper whole lake averages. Samples which are collected at the surface or as euphotic zone composites during stratification should not be included in estimates of ice free TP since they would not allow for elevated hypolimnetic TP concentrations. More detailed information concerning the collection of volume weighted samples is included in the section on sample collection.

TP_{so} and TP_{if} values may differ due to; the resuspension of sediment phosphorus at spring turnover in shallow lakes, the contribution of TP accumulated under ice to spring values or the loss of phosphorus to the sediments through the settling of algal cells during stratification (Dillon *et al.* 1986). For this data set, however, the two values are in relatively close agreement. The relationship between TP_{so} and TP_{if} (14 year average) for 9 lakes is shown in Figure 2. The regression shown in Figure 2 is slightly different from the one outlined in the Trophic Status Report of Ontario's Lakeshore Capacity Study (Dillon *et al*

1986) since it is derived from a greater number of lakes and includes more recent data. The Trophic Status Report outlines equations to convert total phosphorous concentrations from one sampling regime to another, ie. TP_{if} to TP_{so} (see Appendix 1).

Average epilimnetic phosphorus (TP_{epi}) measured during stratification is sometimes reported. Samplers who cannot collect volume weighted samples often report epilimnetic TP for the stratified season and conversions can then be made from these values to ice free values using the formulae in Appendix 1. Molot and Dillon used TP_{epi} to predict chlorophyll a (see Appendix 2.)

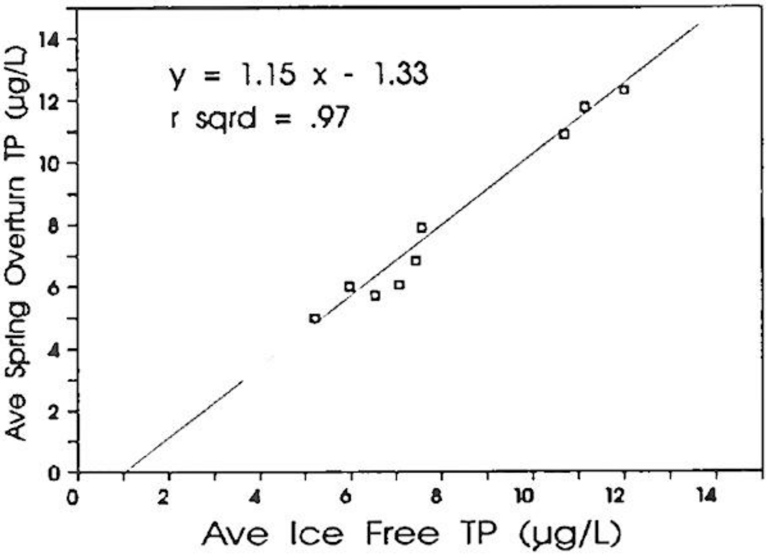

Figure 2: The relationship between spring overturn TP and ice free TP concentrations (14 year average) or the 9 lakes in Table 1.

Sampling for the Estimate of Spring Overturn Phosphorus

Spring overturn total phosphorus (TP_{SO}) values are a favoured measure of the phosphorus content in lakes because:

1. They do not encompass any seasonal variability;
2. They represent whole, mixed lake conditions, and
3. They can be obtained with a single sample.

Nevertheless, a single measure of TP_{SO} has one drawback. Any sampling or analytical error associated with the measurement will not be detectable, since there are no other measures with which to compare it.

Spring overturn values also show year-to-year variability (Knowlton *et al.*,1984, Hutchinson et al., 1991). Although TP_{SO} values are often based on a single measurement, it is recommended that these values be reported as the average of several years of data. This will avoid problems associated with the use of a single measurement to describe a long-term condition. Precision of analysis, sampling protocol and variations in the completeness of mixing in the lake (especially in smaller lakes) may all contribute to the year-to-year variability.

The range, mean, standard deviation, and coefficient of variation for spring turnover values are given for 9 lakes for 14 years in Table 1. These numbers are based on single spring overturn measurements in each of the 14 years (n=14). The range in the coefficient of variation (cv) for spring turnover values determined for the 9 lakes is between 0.11 and 0.21 (cv = SD/mean or relative standard deviation). Using formulae from Green (see Appendix 5), estimates of the long-term mean TP_{SO} concentration can be obtained to within 20% accuracy with between one and four years of sampling (see Table 1). Accuracy to within 10% of the long-term mean requires between 5 and 18 years of sampling. The average number of years of TP_{SO} data required for the nine lakes to be within 10 or 20 percent of the long term mean were 10 and 2 samples, respectively. There was no significant relationship between mean TP_{SO} concentrations and the number of years of data required to be within a specific percent of the mean for these study lakes. Thus year to year variability within each lake was more important than lake to lake variations in the TP_{SO} concentrations in determining the sampling effort required to obtain an accurate estimate of the long term mean.

These results are summarized in Table 11.

Table 1: Spring overturn TP data for 9 lakes for 14 years showing range, mean, standard deviation and coefficient of variation. Number of years of data required to be within 10 & 20% of the long term mean (95% confidence) is shown for each lake.

Spring Overturn Total Phosphorus 1976 to 1989

	Blue Chalk	Chub	Crosson	Dickie	Harp	Henry	Plastic	Red Chalk East	Red Chalk Main	
min	4.00	8.74	7.32	8.20	6.10	5.10	3.60	5.40	3.75	
max	6.97	13.53	14.65	16.85	11.00	7.48	7.80	8.09	6.75	
mean	5.71	10.89	11.76	12.31	7.88	6.04	5.99	6.81	4.97	
SD	0.82	1.60	2.01	2.28	1.16	0.68	1.24	0.83	0.76	
cv	0.14	0.15	0.17	0.19	0.15	0.11	0.21	0.12	0.15	
Number of Years of Data Required										Ave
10% mean	8	9	12	14	9	5	17	6	9	10
20% mean	2	2	3	3	2	1	4	1	2	2

Table 2: Ice -free TP data for 9 lakes for 14 years showing range, mean, standard deviation and coefficient of variation. Number of years of data required to be within 10 & 20% of the long term mean (95% confidence) is shown for each lake.

Ice Free Average Total Phosphorus 1976 to 1989

	Blue Chalk	Chub	Crosson	Dickie	Harp	Heney	Plastic	Red Chalk East	Red Chalk Main	
min	5.53	8.84	9.88	10.18	6.77	6.47	4.73	6.60	4.51	
max	7.84	12.51	12.43	14.36	8.92	8.44	8.17	8.96	6.06	
mean	6.54	10.69	11.13	12.00	7.56	7.07	5.97	7.44	5.21	
SD	0.69	1.36	0.83	1.34	0.58	0.66	1.05	0.67	0.41	
cv	0.11	0.13	0.07	0.11	0.08	0.09	0.18	0.09	0.08	
Number of Years of Data Required										Ave
10% mean	4	6	2	5	2	3	12	3	2	5
20% mean	1	2	1	1	1	1	3	1	1	1

Sampling for the Estimate of Ice-Free Phosphorus

Ice-free mean total phosphorus concentrations (TP_{if}) require the collection of several samples over the course of the ice-free season. It is therefore necessary to determine the number of samples required within a given year in addition to the number of years of data required to approximate long term means. Although more sampling effort within each year is required for estimating TP_{if} than for TP_{SO} the data are less variable on a year-to-year basis, so that fewer years of sampling are required (Table 2). TP_{if} values for 9 lakes for 14 years with range, mean, standard deviation and coefficient of variation are shown in Table 2. Using these data, the number of years of sampling required to yield ice-free means that are within 10% or 20% of the true mean 95% of the time can be calculated. About half the number of ice-free means are required compared to spring overturn values to achieve the same accuracy relative to the long-term mean. The average number of years of TP_{if} data required to be within 10% or 20% of the long term mean are 5 and 1 respectively. Note: The above estimates of sampling effort assume that sufficient numbers of samples have been taken within each year to derive accurate annual ice free means.

TP_{if} must be derived from a sufficient number of samples within a given year to account for seasonal variation in the phosphorus concentrations. In addition, during stratification volume weighted samples must be collected to account for variations in the concentrations in each stratum and to ensure that stratified season samples will represent whole lake averages, (each sample will combine water from different depths in volumes proportional to the volume of water at each corresponding depth in the lake, see 'Sampling Methods').

To determine the frequency of sampling required for reliable estimates of TP_{if} during a single year, TP measurements from a 14 year period for Harp, Dickie and Blue Chalk lakes were analyzed. These lakes were sampled between 5 and 27 times during the stratified season of each year from 1976 to 1989. The results indicate that Harp lake would require an average of 7 volume weighted samples per season to be 95% confident of being within 10 % of the mean. Blue Chalk would require 9 samples and Dickie would require 11. In addition, each estimate would require one spring and fall turnover sample, so between 9 and 13 visits are necessary to be within 10 % of the long-term mean. This indicates that approximately two samples per month during stratification plus one sample at each of the spring and fall turnovers would be required to be within 10% of the long term mean. Monthly sampling would provide estimates that were within 20% of the long term mean. These results are summarized in Table 11.

Sampling for the Estimate of Epilimnetic Phosphorus

Some models use TP_{epi} values to predict chlorophyll levels. TP_{epi} is also the estimate generated by sampling programs where volume weighting apparatus is unavailable, and surface grab or 5 meter composite samples are taken.

The variation in TP_{epi} estimates are intermediate between those for TP_{SO} and TP_{if}. TP_{epi} means for 9 lakes over 14 years are shown in Table 3. Estimating TP_{epi} with 95% confidence to within 10 or 20% of the long-term mean requires an average of seven and two years, respectively. Note that these estimates of sampling effort assume that sufficient samples have been taken within each year to obtain accurate annual means.

The number of samples required within each year to be within 10 or 20 % of the mean are shown for 4 lakes in Table 4. Note that the mean coefficient of variation between lakes is relatively constant such that recommended sample numbers will apply to all of the observed lakes. Five samples per stratified season (monthly sampling) will yield an estimate within 20% of the long-term mean. Nineteen samples (weekly sampling) will give an estimate within 10% of the long-term mean.

Collection of Total Phosphorus Samples

Sampling Methods

When a lake is completely mixed, samples taken from one depth or location should not differ greatly from those taken elsewhere in the lake. For this reason the sampling methodologies for TP_{SO}, need not be as rigid as they would be for volume weighted samples collected during the stratified period. Spring or fall overturn samples are usually collected as composites of the upper 5 meters of the water column near the deepest location in the lake (Nearshore areas or isolated embayments may not display values that are typical of whole lake values even though the lake is considered 'theoretically' to be mixed). This is accomplished using a 5 meter long 2 inch ID (¼" wall) Tygon hose which is lowered into the water column. The top of the hose is then crimped and the bottom of the hose is pulled up on a tether to retain the contents. The entire contents of the hose are then transferred to a clean polypropylene carboy or bucket to ensure mixing before subsampling into containers for submission for analysis. In some cases weighted 'composite' bottles are used to collect samples for the upper 5 meters (Neary and Clark 1992). These are lowered and raised through the five meter water column as the bottle fills to sample water in even proportions from the surface to a depth of 5 metres.

Table 3: Epilimnetic TP data for 9 lakes showing range, mean, standard deviation and coefficient of variation for 14 years of data. Number of years of data required to be within 10 & 20 % of the long term mean (95% Confidence) is shown for each lake.

	Blue Chalk	Chub	Crosson	Dickie	Harp	Heney	Plastic	Red Chalk East	Red Chalk Main	
min	4.19	6.41	7.34	8.64	5.72	6.32	3.32	4.28	3.41	
max	6.34	10.62	10.05	13.69	8.29	7.23	6.98	5.54	5.40	
mean	4.89	7.71	8.78	10.85	6.59	6.64	4.78	4.84	4.45	
SD	0.62	2.40	0.80	1.52	0.69	0.42	1.04	0.44	0.52	
cv	0.13	0.31	0.09	0.14	0.11	0.06	0.22	0.09	0.12	
Number of Years of Data Required										Ave
10% mean	6	8	3	8	4	2	19	3	5	7
20% mean	2	2	1	2	1	1	5	1	1	2

Table 4: The annual means, standard deviations and coefficients of variation for TP_{epi} samples for four lakes for 14 years showing the number of samples required each year to be within 10 & 20 % of the long term mean.

	Blue Chalk					Ave cv = 0.23								
	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
mean	5.63	6.34	5.57	5.06	4.88	4.56	4.88	5.22	4.52	4.77	4.22	4.19	4.22	4.28
SD	1.67	1.49	1.69	1.56	0.86	1.33	1.00	2.06	0.84	0.78	0.75	0.71	0.58	0.42
cv	0.30	0.24	0.30	0.31	0.18	0.29	0.21	0.40	0.19	0.16	0.18	0.17	0.14	0.10
n	17	27	21	24	23	23	14	13	12	13	6	8	6	4
	Dickie					Ave cv = 0.23								
mean	13.48	11.38	12.13	13.69	11.97	10.13	10.06	10.08	8.90	10.51	10.20	9.86	8.64	6.18
SD	2.47	1.80	1.57	4.00	3.30	2.34	1.09	1.67	1.68	3.93	0.75	2.55	2.37	3.03
cv	0.18	0.16	0.13	0.29	0.28	0.23	0.11	0.17	0.19	0.37	0.07	0.26	0.27	0.49
n	12	22	23	25	20	20	11	11	11	11	5	7	5	5
	Chub					Ave cv = 0.21								
mean	9.08	8.97	10.66	8.66	10.07	8.97	8.10	7.47	7.89	7.35	7.32	6.41	7.33	7.66
SD	2.21	2.09	3.60	1.67	2.33	1.68	1.56	1.59	1.81	0.70	0.78	1.96	1.33	1.62
cv	0.24	0.23	0.34	0.19	0.23	0.19	0.19	0.21	0.23	0.09	0.11	0.31	0.18	0.21
N	16	28	22	27	22	23	13	12	13	11	8	9	6	5
	Harp					Ave cv = 0.21								
mean	7.31	7.52	6.18	6.41	8.29	6.48	6.64	6.20	5.77	6.52	6.62	6.15	5.72	5.70
SD	2.40	1.60	1.58	1.68	1.66	1.29	0.70	1.18	1.56	0.60	1.07	2.32	0.92	1.07
cv	0.33	0.21	0.26	0.26	0.20	0.20	0.11	0.19	0.27	0.09	0.16	0.38	0.16	0.19
n	15	32	26	29	22	25	12	13	12	12	10	12	12	8

Average number of samples per year (all lakes) with 95% confidence of being

- within 10% of mean = 19 (cv = 0.22)
- within 20% of mean = 5 (cv = 0.22)

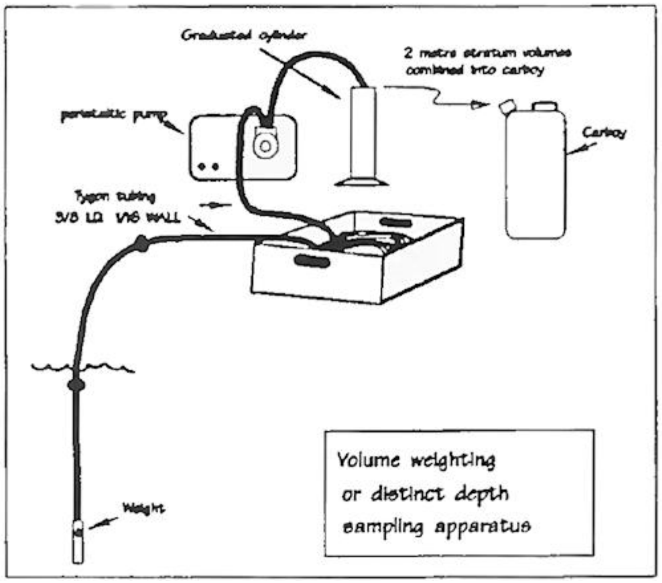

Figure 3: Volume weighted sampling apparatus.

Composite samples collected during the stratified season must be volume weighted. This requires the calculation of the volume of water in each stratum of the lake (Nicolls *et al.*, 1983). Samples are then taken from each 2 meter lake stratum in volumes which are proportional to the volume of water in the lake at that depth. The two meter stratum subsamples are then pooled to provide a volume weighted, whole lake sample and may be combined in the required number to represent epi, meta or hypolimnetic samples if required. Staff at the DRC, collect samples from each depth stratum with a peristaltic pump and tygon tubing. The sampling apparatus is shown in Figure 3.

Common Sampling Problems

At present there are two common sampling methods for total phosphorus. Many samplers collect water samples into 500 ml polyethylene (PET) bottles, while others collect samples directly into the borosilicate glass, screw cap test tubes that are used for digestion in the lab. Comparisons between these two methods yield different results. Samples submitted in 500 ml PET bottles must be subsampled into borosilicate glass digestion tubes upon arrival at the lab. There has long been concern, especially for low level samples, (TP <20 µg.L^{-1}) that this subsample would not be representative of the original sample. Phosphorus will be assimilated by any bacteria residing in the sample. Although this does not present analytical problems (the bacteria release the phosphorus in the digestion process) problems can arise during the transfer of sample from the sampling container to the analytical vessel. Bacteria or algae that are attached to the walls of the PET bottle contain phosphorus which is not represented in the subsample for analysis. These are conditions which cannot normally be overcome by shaking samples, since the bacteria and algae adhere strongly to the container wall. The result is a consistent underestimate of the TP in the sample.

The severity of this problem is related to sample origin, temperature, and time between collection and analysis. Dilute samples collected in spring or fall normally have low bacterial concentrations, which minimizes the potential for problems. Similarly, very cold samples or samples which are kept refrigerated prior to analysis would also minimize subsampling errors. Finally, samples which are promptly analyzed show fewer problems relative to those which are held for long periods prior to analysis. Unfortunately these factors contribute to general underestimates of the total P which can range from a few percent to 30 or 40 percent of the TP, depending on the combined contributions of all of these factors.

It is therefore strongly recommended that sampling for phosphorus be done in the tubes in which the digestion will take place, that they be refrigerated, and that they be analyzed as quickly as possible.

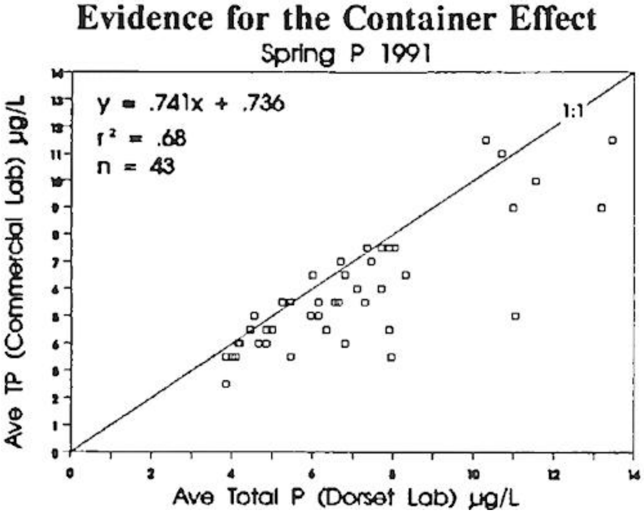

Figure 4: Spring phosphorus data showing the relationship between samples submitted to a commercial lab in PET bottles and to the DRC lab in borosilicate tubes.

Three separate container comparisons were conducted during the 1991 sampling season. In the spring of 1991, samples from 50 lakes sampled at spring turnover were submitted both to a commercial lab in 500 ml PET bottles, and to the DRC lab in borosilicate tubes. The results are shown in Figure 4. The results obtained from the subsamples out of PET bottles were significantly lower than those which were collected and digested in the same tubes. The loss of TP from the samples was not related to differences in quality control between the two labs.

A second comparison was conducted in the spring of 1991 to evaluate the container effects at higher TP concentrations. Seventeen lakes in the Parry Sound District were sampled by MOE Northeastern Region staff using both methods. The borosilicate tubes were returned to Dorset for analysis and the PET bottles were shipped to the MOE lab in Thunder Bay. The results are shown in Figure 5. These results are in closer agreement, probably due to cold sample temperatures and prompt shipping to the lab.

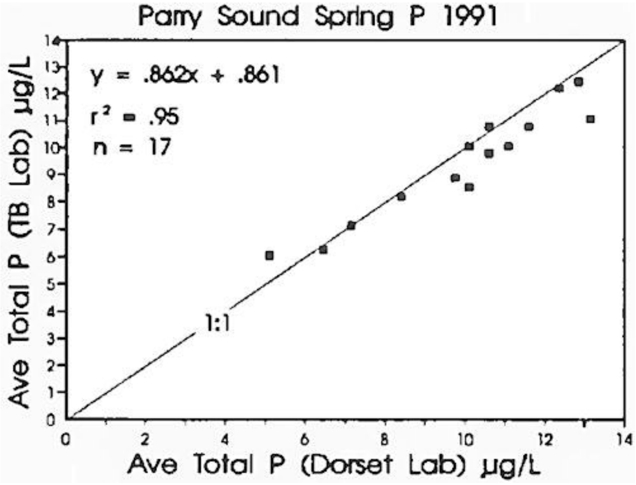

Figure 5: Spring phosphorus comparison study data showing the relationship between samples submitted to the Thunder Bay MOE lab and samples submitted to the Dorset lab. Lakes sampled were from the Parry Sound District.

Again, however, most samples are either on or below the 1:1 line which suggests some loss of phosphorus as a result of the subsampling process.

Finally, several lakes were sampled in the Dorset area in the late summer of 1991 (early September). Water temperatures were >20°C. Samples were also collected and held for shipment to the Thunder Bay lab at week's end. This would ensure maximum times between collection and analysis to illustrate the potential for a worst case scenario. The results are shown in Figure 6. Total P losses were in the range of 30 to 40 percent.

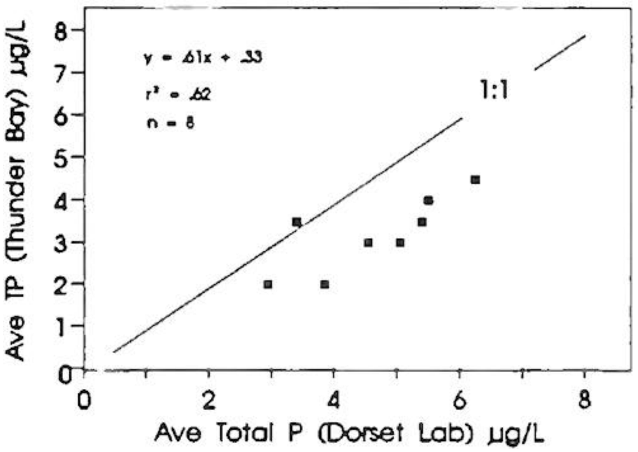

Figure 6: Late summer phosphorus data compared as in Fig 5. Lakes were sampled in warm weather, and deliberately delayed or one week prior to analysis.

Estimating Chlorophyll a

The amount of algae in the water column is often used as a trophic status indicator because it is the most noticeable visual consequence of eutrophication (Smith 1985, Walker 1985). Chlorophyll a is a surrogate measure of algal biomass (Nicholls and Dillon 1978) and is frequently predicted by trophic status models (see Appendix 2).

Like phosphorus, chlorophyll concentration can be measured from many different seasons and depths. There are, however, significant differences to consider. Single spring overturn chlorophyll values, Chl_{SO} for example, are of little use since they may represent either the highest or lowest chlorophyll concentrations of the year. This is because chlorophyll concentrations peak at different times in oligotrophic lakes and eutrophic lakes. Eutrophic lakes commonly display spring and fall blooms whereas oligotrophic lakes do not (Marshall, 1989). The combination of individual measurements to form seasonal or annual means for chlorophyll must therefore be performed with some caution. Since it is impractical for many studies to include under ice measurements, most sampling strategies are directed at estimating ice-free or stratified season means. These two chlorophyll estimates are closely related, as shown in Figure 7.

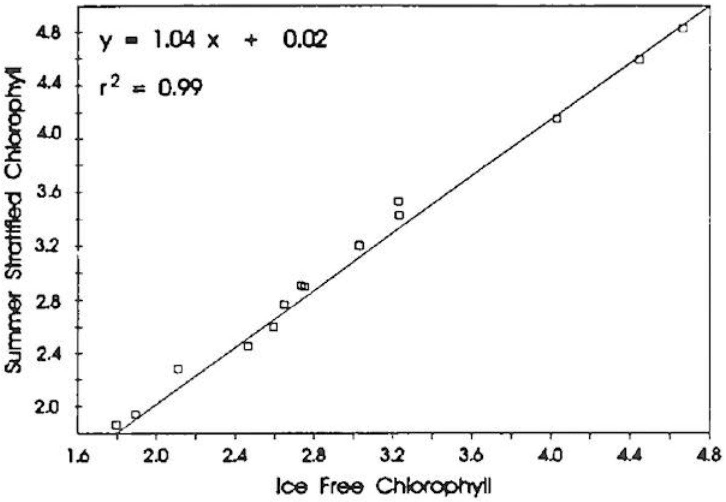

Figure 7: The relationship between mean summer stratified (Chl_{ss} and ice free (Chl_{if}) chlorophyll determined for 14 Dorset lakes for 13 years.

Seasonal, Annual and Spatial Variation of Chlorophyll

Chlorophyll a levels in a lake can vary considerably during the year (Marshall 1989, Hanna 1991, Knowlton 1984). Figure 8 shows ten years of chlorophyll data (grouped by month) for Harp, Dickie and Blue Chalk Lakes.

In more eutrophic lakes, spring blooms may cause Chl_{SO} values to be higher than Chl_{ss} values. The absence of spring blooms in oligotrophic lakes would produce the opposite result. Table 5 shows the differences in chlorophyll estimates from different sampling strategies for 14 oligo- to mesotrophic lakes. In most cases ice-free and summer stratified values are comparable, but this would probably not be the case if spring or fall blooms were observed.

Both Ch_{if} and Chl_{ss} values may show considerable year-to-year variation (Knowlton 1984, Smeltzer 1989). Annual variation in average ice-free chlorophyll for 14 lakes for 12 years is shown in Table 6 and shown graphically for Blue Chalk, Harp and Dickie lakes in Figure 9.

In addition, chlorophyll concentrations vary vertically within the water column (Hanna, 1991) and may vary spatially, especially in large lakes (Neary and Clark 1992).

Chlorophyll 1976-1988

	Mean				Standard Deviation			
	(ss)	(if)	(so)	(fo)	(ss)	(if)	(so)	(fo)
Basshaunt	2.60	2.60	2.20	2.02	0.95	0.94	0.90	0.78
Bigwind	3.20	3.03	1.58	2.74	0.92	0.80	0.96	1.16
Blue Chalk	1.94	1.89	1.19	2.36	0.18	0.16	0.51	0.64
Buck	2.45	2.46	2.49	2.28	0.46	0.56	1.42	0.81
Chub	3.42	3.23	1.69	3.05	1.09	1.08	1.24	3.27
Crosson	2.77	2.65	1.63	2.28	0.66	0.64	0.53	1.22
Dickie	4.83	4.66	3.48	3.89	0.94	1.20	3.16	2.18
Glen	4.15	4.03	5.36	2.59	2.17	1.78	2.27	0.64
Gullfeather	4.60	4.45	2.81	4.52	0.66	0.69	1.20	1.83
Harp	3.53	3.23	1.20	2.51	0.71	0.52	0.35	0.68
L. Clear	2.90	2.75	1.95	2.20	0.56	0.63	0.89	1.24
Red Chalk	2.28	2.11	1.01	1.75	0.37	0.33	0.42	0.57
Solitaire	1.86	1.80	1.45	1.84	0.30	0.26	0.61	0.43
Walker	2.91	2.73	1.39	2.91	0.87	0.83	0.38	1.06
AVG	3.10	2.97	2.10	2.64	0.77	0.75	1.06	1.18

Table 5: Stratified season, ice-free, spring overturn and fall overturn chlorophyll values for 14 lakes (12 year mean) including standard deviations.

Table 6: Variations in ice-free chlorophyll a for 14 lakes for 12 years.

	Basshaunt	Bigwind	Blue Chalk	Buck	Chub	Crosson	Dickie	Glen	Gullfeather	!tarp	Little Clear	Red Chalk	Solitaire	Walker
76.77	2.13	1.84	1.92	1.94	3.45	3.37	4.34	1.60	4.67	2.71	2.46	2.10	2.18	2.37
77.78	1.07	2.64	1.85	1.43	1.99	1.66	5.85	3.00	4.99	2.78	2.21	1.75	1.77	1.80
78.79	1.78	2.94	1.67	1.97	4.65	2.55	5.66	2.90	4.93	2.42	2.31	2.09	1.40	2.20
79.80	2.29	2.46	1.89	3.74	2.26	1.81	5.02	3.57	3.66	3.08	1.69	2.01	1.51	2.81
80.81	2.90	2.96	2.11	2.97	5.59	3.18	4.57	6.64	4.81	3.42	3.17	2.72	1.79	3.00
81.82	2.10	2.30	2.10	2.88	3.56	1.87	3.67	3.91	3.30	2.84	2.10	2.49	1.60	3.24
82.83	2.32	2.63	1.58	2.20	3.87	3.07	3.09	3.92	4.60	3.96	2.87	1.85	2.25	2.22
83.84	4.50	3.30	1.81	2.47	1.81	2.76	6.67	3.96	5.68	2.93	3.80	2.24	1.97	2.15
84.85	2.53	3.47	1.99	2.35	2.69	3.31	3.92	2.28	4.80	3.30	3.02	2.48	1.47	1.60
85.86	2.83	4.43	1.99	2.41	2.98	2.85	6.45	3.50	3.31	3.31	2.41	1.87	1.83	4.16
86.87	4.38	4.70	1.76	2.76	2.26	1.92	3.31	8.36	4.53	4.29	3.54	1.50	2.05	4.36
87.88	2.31	2.69	2.03	2.45	3.65	3.44	3.41	4.70	4.07	3.68	3.45	2.22	1.73	2.90
AVG	2.60	3.03	1.89	2.46	3.23	2.65	4.66	4.03	4.45	3.23	2.75	2.11	1.80	2.73
SD	0.94	0.80	0.16	0.56	1.08	0.64	1.20	1.78	0.69	0.52	0.63	0.33	0.26	0.83
cv	0.36	0.26	0.08	0.23	0.34	0.24	0.26	0.44	0.16	0.16	0.23	0.16	0.15	0.30

Sampling Frequency

Estimating an Annual Mean

There have been many attempts to define the optimum number of samples required each year to account for temporal variations in chlorophyll a (Knowlton 1984; Marshall 1988; Kwiatkowski 1985). Chlorophyll data for three of the Dorset study lakes are presented in Tables 7, 8, and 9. In these cases, trophic status appears to influence the number of samples required to be within specified percents of the mean (mesotrophic Dickie Lake requires more samples than oligotrophic Blue Chalk Lake), but this may not be generally true. Marshall found that 'trophy has little effect on the sampling effort required to achieve pre-determined levels of precision for lakes sampled year round (1989). Temporal variance was found to increase in proportion to the square of the mean, giving a constant coefficient of variation. Both eutrophic and oligotrophic lakes had comparable temporal variation. These findings were in agreement with those of other researchers as outlined by Marshall (1988).

Marshall (1988) estimated that bias in sampling for chlorophyll a was significantly reduced after the collection of 5 samples per year and that 10 observations would give 95% confidence of being within approx 20% of the mean. Confidence intervals of 10% would require 30 to 50 samples. These findings generally agree with the sample numbers in Tables 7 to 9. Similar numbers were derived for Lake Ontario by Kwiatkowski (1985) i.e: 20% with 5 and 10% with 20 samples. It appears that a minimum of 5 and ideally 10 samples per year are required for Chl a estimation. The results are summarized in Table 11.

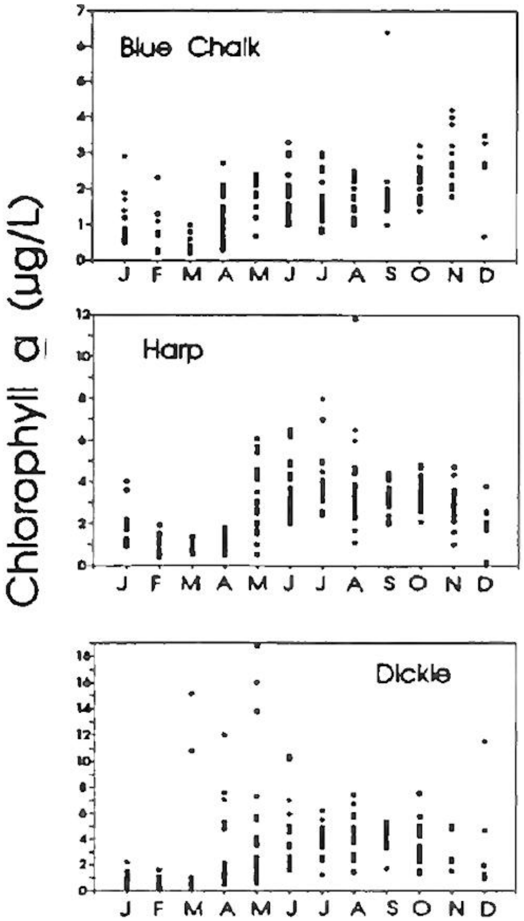

Figure 8: Monthly range in chlorophyll data or ten years or Blue Chalk, Harp and Dickie lakes.

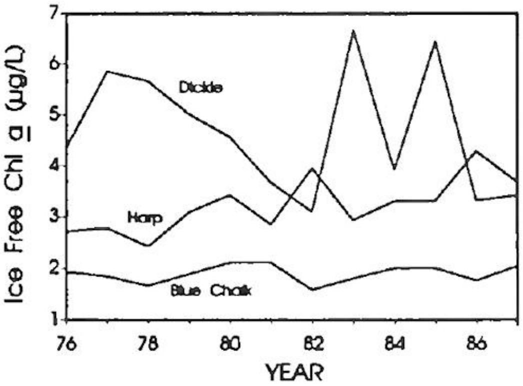

Figure 9: Mean ice free chlorophyll (Ch_{if}) or Blue Chalk, Harp, and Dickie Lakes from 1976 to 1987.

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	Mean
meta	1.88	1.85	1.67	1.84	2.08	2.10	1.51	1.76	1.96	2.01	1.87
ad	0.70	0.58	0.88	0.57	0.44	1.17	0.50	0.43	0.70	0.68	0.18
cv	0.37	0.32	0.53	0.31	0.21	0.56	0.33	0.25	0.36	0.34	0.09
n	24	27	23	27	25	25	16	16	17	20	
Number of samples Required Each Year											Mean
10% mean	56	40	111	38	17	124	44	24	51	45	55
20% mean	14	10	28	10	4	31	11	6	13	11	14
50% mean	2	2	4	2	1	5	2	1	2	2	2

Number of Years of Data Required

mean	1.86 (10 year)
ad	0.17 (10 year)
cv	0.09
10% mean	3
20% mean	1
50% mean	1

Table 7: Chlorophyll data for 10 years for Blue Chalk Lake showing the number of samples required each year and the number of years required to be within 10, 20 and 50 % of the long term mean.

	1976	*977*	1978	1979	1980	1991	1982	1982	1984	1985	Mean
mean	2.71	2.78	2.24	3.08	3.33	2.82	3.74	2.79	3.05	3.30	2.99
ad	0.87	1.22	0.86	1.21	0.95	0.86	1.74	1.10	1.23	1.36	0.39
cv	0.32	0.44	0.39	0.39	0.28	0.31	0.46	0.39	0.40	0.41	0.13
n	21	25	27	28	25	28	16	18	16	21	
Number of samples Required Each Year											Mean
10% mean	41	*77*	59	62	32	38	86	62	65	68	59
20% mean	10	19	15	16	8	9	21	15	16	17	15
50% mean	2	3	2	2	1	2	3	2	3	3	2

Number of Years of Data Required

mean	2.99 (10 year)
d	0.39 (10 year)
cv	0.13
10% mean	7
20% mean	2
50% mean	I

Table 8: Chlorophyll data for 10 years for Harp Lake showing the number of samples required each year and the number of years required to *be* within 10, 20 and 50 % of the long term mean.

	1976	1977	1978	1979	1980	1981	1982	1983	1994	1985	Mean
mean	4.51	5.73	5.60	5.02	4.43	3.67	2.97	6.40	4.21	5.40	4.79
ad	3.12	2.77	2.76	2.59	2.84	1.51	0.99	4.22	2.40	3.74	0.98
cv	0.69	0.48	0.49	0.52	0.64	0.41	0.33	0.66	0.57	0.69	0.21
n	21	25	27	27	24	24	15	17	16	19	
Number of Samples Required Each Year											Mean
10% mean	191	93	97	106	164	67	44	174	131	192	126
20% mean	48	23	24	27	41	17	11	43	33	48	32
50% mean	8	4	4	4	7	3	2	7	5	8	5

Number of Years of Data Required

mean	4.79 (10 year)
ad	0.98 (10 year)
cv	0.21
10% mean	16
20% mean	4
50% mean	1

Table 9: Chlorophyll data for 10 years for Dickie Lake showing the number of samples required each year and the number of years required to be within 10, 20 and 50 % of the long term mean.

Sampling frequency should reflect the intended use of the data. For example, increased effort is required if the intent is to observe maximum chlorophyll values (blooms). Since algal blooms are often only days in duration, even frequent sampling programs can fail to record the true maxima. If maximum values are of interest then sampling intervals should be increased at those times of the year when blooms are expected. This approach, however, will produce biased estimates of annual or ice free means.

Estimating the Long-Term Mean

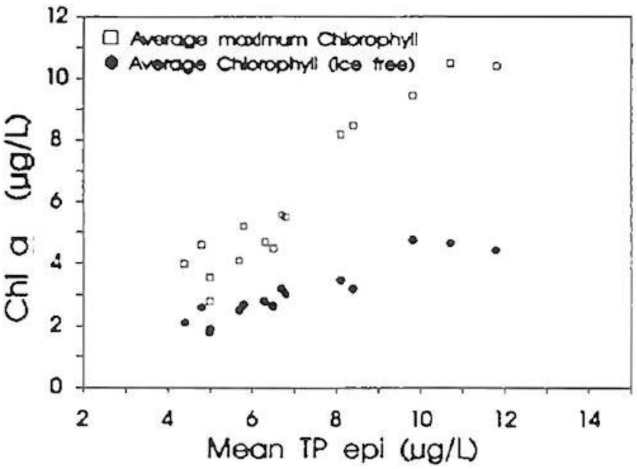

Figure 10: The relationship between long term mean TP_{epi} and average and maximum average chlorophyll.

Many researchers have shown that several years of chlorophyll data must be collected to adequately describe the long term mean (Molot and Dillon 1991, Knowlton 1984, Smeltzer 1989, Trautmann 1982, Knowlton 1984). Knowlton (1984) suggests the collection of seven samples per year for four years to obtain a 90% probability of detecting a two fold difference between two lake means. Data from Blue Chalk, Harp and Dickie lakes indicate estimates within 20% of the long term mean with the collection of 1, 2 and 4 years of data respectively. Molot and Dillon required the average of at least 6 years of data for individual lakes to yield a significant relationship between annual TP_{epi} and annual average chlorophyll concentrations. (Figure 10). Generally, a minimum of 4 to 5 years of data appears to be necessary for estimating the long-term mean chlorophyll concentration of a lake. This gives estimates that would be between 10 and 20% of the long-term mean for most lakes.

As noted earlier, however, maximum chlorophyll conditions are transient, and are likely to be missed by all but the most intensive sampling programs. Maximum chlorophyll conditions would probably be better expressed as 'predicted' mean maximum values based on steady state models. The relationship between average maximum observed chlorophyll and TP_{epi} for the Dorset lakes is shown in Figure 10.

The model currently being used by MOE Dorset to predict ice-free mean chlorophyll concentration from phosphorus is outlined in Appendix 2.

Collection of Samples

Chlorophyll is heterogeneously distributed with depth but more homogeneously distributed spatially within a given lake (Hanna 1991). Hanna found that different depth integrating protocols yield different results and suggested the collection of integrated tube composite samples from the euphotic or trophogenic zone. Volume weighted sampling did not produce any further precision in the results.

Sampling in different locations on lakes is required where there is evidence of spatial variations in chlorophyll. This can be the case where major embayments have a nutrient status that differs from the rest of the lake (Neary and Clark 1992). This can result from major inflows that are either more enriched or dilute than the main lake. Spatial variations over the surface of the lake are also common in convoluted or dendritic lakes that have a number of different land use patterns in the catchment.

Samples are usually collected into 1 litre opaque Nalgene bottles and fixed immediately with 1 ml of saturated magnesium carbonate. Refrigeration followed by analysis within a few days is recommended.

Algal Enumeration

Many programs submit samples for algal enumeration on a regular basis to observe seasonal or long term trends in algal biomass. The enumeration of algal samples is a labour intensive and expensive process and it has been suggested (Ken Nicholls, Limnology Section, Rexdale, pers comm.) that in many cases seasonal samples could be pooled and analyzed as time composites. This can provide average ice-free information with less cost and effort.

Measuring Oxygen Profiles

The depletion of oxygen below the thermocline has been shown to be primarily influenced by lake morphometry (Molot *et al.* 1992). However, within individual lakes the depletion of oxygen in the hypolimnion will increase in response to increases in the nutrients. Cold water fish species such as lake trout have high dissolved oxygen requirements and significant depletion of hypolimnetic oxygen is of particular concern for lake trout lakes.

Hypolimnetic oxygen concentrations are also of interest when modelling phosphorus in a lake. Sediment phosphorus dissolves under anoxic conditions, and the resuspension of this phosphorus must be considered when predicting the phosphorus concentrations in lakes.

Seasonal and Annual Variation

Lakes which turn over in the spring usually show oxygen saturation from top to bottom prior to the onset of stratification. Incomplete mixing is often observed in smaller lakes but is rare in larger lakes. As the season progresses, the oxygen profiles will reflect oxygen consumption in the hypolimnion as a function of lake morphometry and trophic status. Since the re-supply of oxygen to the bottom waters does not occur during stratification, there is a steady decrease in hypolimnetic oxygen concentration over the course of the stratified season. A progressive erosion in oxygen profiles from the onset of stratification until fall turnover is common. Very large and deep lakes will be the exception to this rule. Many larger oligotrophic lakes maintain oxygen concentrations near saturation from top to bottom all year long.

Hypolimnetic oxygen concentrations are usually at a minimum just prior to fall turnover. Measures of critical lake trout habitat usually focus on these minimal conditions (Evans *et al.* 1991). The Malot *et al.* (1992) oxygen model predicts oxygen profiles for the first week in September (see Appendix 3).

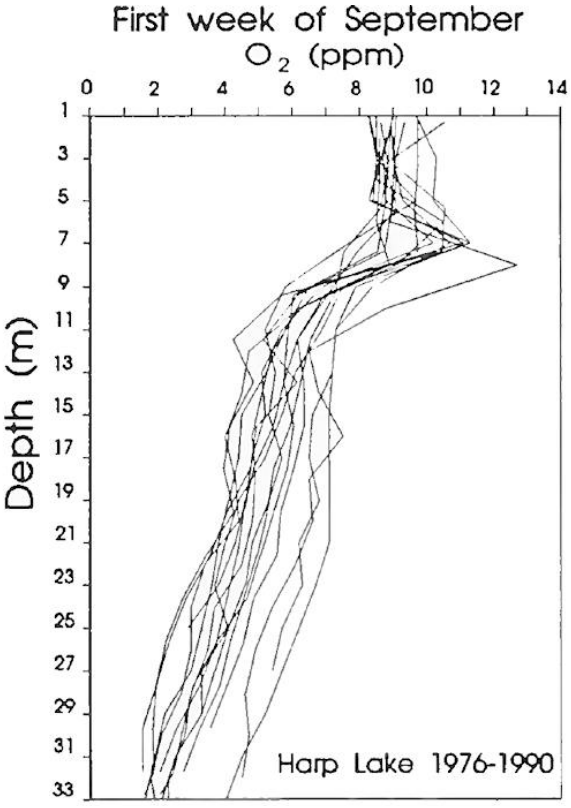

Figure 11: Oxygen profiles observed for the first week in September or Harp Lake or 15 years.

In some cases, the lake may show complete and drastic oxygen depletion in the bottom waters soon after the onset of stratification. In these cases there may be some interest in monitoring profiles over the entire season to determine 'how early' the condition develops. In most cases, however, lakes which display early and drastic oxygen depletion in the hypolimnion do not support a cold water fishery.

Lakes will display some year-to-year variation in the oxygen profiles observed on a given date. Variations in the September profiles for 15 years on Harp Lake are shown in Figure 11. No relationship could be observed between climatic or environmental conditions observed during the stratified season and the nature of these fall profiles. The degree of mixing observed in the spring has been shown to be a function of the maximum fetch across the area where the mixing is observed (Molot *et al.* 1992). Smaller lakes which do not mix completely in the spring will display specific degrees of mixing determined by environmental factors such as wind and temperature at or prior to turnover. The climatic conditions at this time may therefore ultimately have an effect on the nature of the fall profiles.

The variation in the profiles observed for the first week in September for Harp lake (<1.4 k fetch) over 15 years were shown to be directly related to quantity of oxygen present in the spring and hence the degree of mixing achieved prior to stratification. The relationship between total mass of oxygen below 9 meters for the spring and fall of each year is shown in Figure 12.

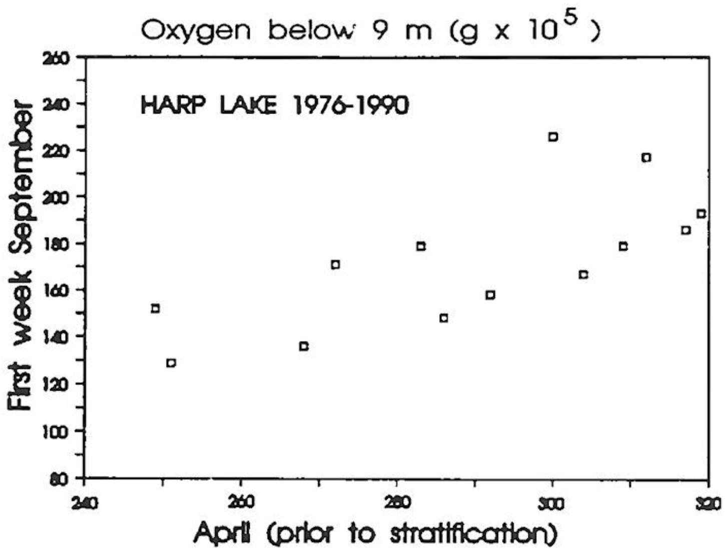

Figure 12: Mass of oxygen below 9 meters, spring vs fall, or 14 years for Harp lake.

Sampling Frequency

Since oxygen profiles show seasonal variation which reflects a progressive depletion of oxygen, most researchers focus on two time periods. Spring profiles are measured to determine the degree of mixing at spring turnover and late summer profiles are observed to determine minimum oxygen conditions. Several years of data will be necessary to ensure that atypical profiles are not being used to represent long term average conditions.

Collection of Samples

Some researchers use oxygen meters to determine oxygen profiles in lakes. This will give good results when competent field staff are aware of the pitfalls presented by oxygen meters. Problems occur with long equilibrium times at low oxygen concentrations and with potential membrane poisoning due to the presence of hydrogen sulphide in anaerobic hypolimnion. Where access to a lab is possible it is preferable to submit samples in gas tight bottles for Winkler determination of O_2 to verify measured concentrations below 4 ppm.

Secchi Depth Measurements

Water clarity has long been used as an indication of trophic status because of the established relationship between Secchi disc depth measurements and chlorophyll a. In addition, Smeltzer (1989) found that Secchi depth measurements were less subject to temporal variability than either chlorophyll or phosphorus measurements and as such could provide “a better monitoring tool for early detection of eutrophication”. Dillon and Rigler (1975) described the relationship between mean Chl a and Secchi depth as:

$$SD_{SS} = 5.21 / (Chl_{SS})^{0.41}$$

but noted that the predictive capabilities of the model were poor for lakes with high DOC. Dillon *et al.*, (1986) noted that, for the Lakeshore Capacity Study lakes, a stepwise regression model which tested all of the usual trophic status parameters found Secchi depth (range 2.5 - 6.7 m) to be most highly correlated with DOC (annual mean 2.8-6.9 mg/L). The model picked TP_{SO} as the second significant independent variable and chlorophyll (ice free mean 1.7-5.3 µg/L) as the third significant variable. The relative importance of TP as a factor in controlling water clarity is therefore dependent on the level of DOC in the water. Within a given lake DOC tends to remain constant between years such that variations in water clarity may reflect changes in phosphorus loads. Dillon *et al.* (1986) noted that TP may be a surrogate “for all particulate material including live phytoplankton, living material other than phytoplankton, and non-living material.”

Table 10 shows that 3-4 observations per year will provide an estimate of Secchi depth to within 20% of the annual mean. Improving the precision to 10% of the mean requires 11 to 17 observations per year. The 14 year mean value can be estimated to within 20% with 1 to 2 years of observation and to within 10% with 2 to 7 years of data.

Researchers should understand that Secchi depth determinations will usually be inadequate when used alone for any kind of trophic status evaluation unless the factors that control water clarity in the lake are clearly understood. The Secchi depth component of the Trophic Status Model described by the Lakeshore Capacity Study is outlined in Appendix 4.

Table 10: The mean, standard deviation, and coefficient of variation for Secchi disc depth data for four lakes for 14 years showing the number of samples required each year and the number of years of data required to be within 10 or 20% of the mean.

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Blue Chalk															
mean	7.16	7.24	5.77	6.53	6.92	6.29	6.50	6.51	6.42	6.58	6.88	7.67	5.82	6.75	Ave cv = 0.18
SD	1.34	1.11	0.80	1.25	1.00	0.97	1.39	1.08	0.97	1.46	1.28	1.82	0.76	1.88	samp/yr =
cv	0.19	0.15	0.14	0.19	0.14	0.15	0.21	0.17	0.15	0.22	0.19	0.24	0.13	0.28	13 (10%)
n	18	32	24	27	25	27	16	17	16	20	11	11	10	9	3 (20%)
Dickie															
mean	2.96	2.98	2.96	2.29	2.49	2.49	3.05	2.67	2.97	2.83	2.55	3.19	2.66	2.63	Ave cv = 0.21
SD	0.43	0.53	0.70	0.37	0.63	0.43	0.61	0.79	0.83	0.38	0.37	0.68	0.70	0.51	samp/yr =
cv	0.15.	0.18	0.24	0.16	0.25	0.17	0.20	0.30	0.28	0.14	0.15	0.21	0.27	0.19	17 (10%)
n	21	29	26	28	23	25	14	16	15	15	10	9	9	8	4 (20%)
Chub															
mean	3.85	3.90	3.01	2.45	2.74	2.91	3.57	3.49	3.32	3.05	2.93	3.85	3.46	3.41	Ave cv = 0.20
SD	0.76	0.80	0.65	0.43	0.49	0.46	0.92	0.80	0.46	0.35	0.61	0.80	0.63	0.95	samp/yr =
cv	0.20	0.20	0.22	0.18	0.18	0.16	0.26	0.23	0.14	0.12	0.21	0.21	0.18	0.28	15 (10%)
n	22	32	25	31	24	28	25	27	25	24	12	11	9	8	4 (20%)
Harp															
mean	4.48	4.32	3.37	3.54	3.49	3.82	3.83	3.80	4.03	3.35	3.54	4.54	3.79	3.82	Ave cv = 0.17
SD	0.66	0.76	0.43	0.65	0.57	0.62	0.41	0.59	0.66	0.66	0.66	0.77	0.68	0.73	samp/yr =
cv	0.15	0.18	0.13	0.18	0.16	0.16	0.11	0.15	0.16	0.20	0.19	0.17	0.18	0.19	11 (10%)
n	20	31	24	30	24	28	16	17	16	19	14	16	14	13	3 (20%)

Years of Secchi data required

	14 yr mean	SD	cv	# years 10%	20%
Blue Chalk	6.65	0.50	0.08	2	1
Dickie	2.76	0.25	0.09	3	1
Chub	3.28	0.43	0.13	7	2
Harp	3.84	0.37	0.10	4	1

Using Historical Data

Problems often arise when researchers attempt to use long term data to explain trends through time. This type of project will only be valid if the older data is comparable to the more recent data. Often there are methodology changes involved with sample collection or analysis that will be significant enough to disallow the comparison of old and new data. Unfortunately there are very few parameters which have not suffered changes in methodology and those measurements normally associated with trophic status have been subject to more changes than most. Researchers must be aware of the dates and significance of any changes in methodology

Phosphorus

The methods used to analyze samples for TP have undergone numerous changes over the years. Most of these have been directed towards improving sensitivity and lowering the detection limit. In addition, laboratories which analyze samples from a variety of sources have instrumentation calibrated to a range of phosphorus concentrations far in excess of those encountered in oligotrophic and mesotrophic lakes. Results from this type of analysis may be questionable especially for oligo-mesotrophic lakes which will fall at the low end of the standard calibration range.

Many long term data sets show a progressive decline in TP values over the past 15-20 years. For example, measurements taken under routine sampling programs on Harp Lake during the early 1970's yielded phosphorus concentrations significantly higher than measurements taken since that time. It is not clear whether these numbers reflect a lowering in the TP concentrations due to the general reduction of anthropogenic phosphorus pollution or simply the increased ability of the labs to precisely measure lower levels of phosphorus. Comparison of these TP results with other trophic status parameters such as algal enumeration or secchi depth might assist researchers who are attempting to unravel trend through time data.

Chlorophyll

The most important methodology change to note for Chlorophyll analysis within the OME labs occurred in June of 1985. The Lab Services Branch switched from the use of 1.2 micron cellulose nitrate filters to 1.2 micron nylon filters. The nylon filters do not dissolve in the solvent used in the extraction process and therefore yield higher recoveries. This would mean that samples analyzed prior to June 85 would generally show lower numbers than those collected after the methods change. Additional uncertainties about the methods change and the temporary privatization of chlorophyll analysis are outlined in Locke (1990).

Oxygen

Historical and recent oxygen determinations by the Winkler titration process are probably comparable. Some caution should be used in the interpretation of any data collected with oxygen meters since the quality of the results tend to be related to the expertise of the operator. Long equilibrium times and the danger of membrane poisoning due to hydrogen sulphide poisoning will potentially affect the accuracy of data collected with oxygen meters when concentrations are below approx. 4 ppm. Older data sets may contain oxygen measurements made by other methods such as Hach kits. These values should be interpreted with caution in cases where the values cannot be verified.

Discussion

This report provides information that will assist managers in the assessment of the trophic status of lakes. The most useful estimate of trophic status, based on both the ease of collection and degree of observed temporal variability, is total phosphorus. Lakes can be characterized by their TP concentrations with minimum effort through the collection of several years of TP_{SO} data. Through more effort within each year, the same lake can be characterized by TP concentrations in fewer years using TP_{if} values.

Because of wider seasonal variation, the accurate estimation of chlorophyll a is more difficult. Many visits are required within a given year and several years of data are required to estimate the long term mean. Average and maximum chlorophyll concentrations are more easily modelled through the collection of lesser amounts of phosphorus data using the Lakeshore Capacity or Molot-Dillon models (Appendix 1 & 2).

Secchi depth is an easy, inexpensive measure of water clarity. Its drawbacks include limited applicability to measuring trophic status, and the subjective nature of the measure. It may be more successfully used for comparisons over time within a given lake than for between-lake comparisons.

Calculations which were used to derive the suitable number of samples should be regarded with some caution. Different statistical methods will yield different results and, more importantly, different data sets may produce different numbers. In many cases, the coefficients of variation are themselves quite varied between lakes. As a result, the average required number of samples may give satisfactory results for most but not all lakes. Caution is especially recommended in cases where the trophic status of the lake in question is generally different than the Dorset set of study lakes.

The required sample frequency will often depend on the intended use of the data. For example, data used to rank a set of lakes by their trophic status would not be required to be as accurate as would data that was collected to observe subtle long term changes in the trophic status of an individual lake. Care should also be taken in the collection of data which is used as inputs or comparisons to steady state trophic status models. These values should adequately account for any temporal variability in the parameter involved.

Often, the practical aspects of sample study design will dictate sample frequencies that are, for example, monthly or weekly and as such will only roughly correspond to the frequencies recommended by the applicable statistics. Nevertheless, the statistics provide a useful guide to the minimum number of samples required to achieve the desired degree of precision.

A summary of the number of samples required for seven of the most commonly used trophic status indicators is shown in the following summary table (Table 11). It should be noted that in many instances even with maximum sampling effort any single year of good data will be on average within 20 % of the long term mean. Most parameters can be measured to within 20% of the mean with reasonable effort but it may not be worthwhile or even possible to expend the effort required to bring the results to within 10% of the true average. Researchers who are analyzing existing data sets can use the guidelines to determine for example how close 3 or 4 spring overturn phosphorous samples would approximate the long term mean and thereby assess the usefulness of historical data.

Table 11: Sample frequencies and protocols.

			samples/year		number of years		
	Derivation	Sample method	95% confidence of being within				time
			10% mean	20% mean	10% mean	20% mean	
TP(so)	usually a single sample	5m composite	1*	1*	10	2	during spring turnover prior to stratification
TP(if)	average of all samples collected for ice free period	composites when lake is mixed volume weighted during stratification	9-13 (bi-weekly)	4-5 (monthly)	5	1	between ice out and freeze up
TP(epi)	average of all samples collected during stratification	epilimnetic composite	19	5	7	2	during stratification
Chl a (ss)	average of all samples collected during stratification ie: self-help programs	euphotic zone composites	less than for Chl(if) should use Chl(if) if spring/fall blooms expected				during stratification
Chl a (if)	average of all samples collected for ice free period	euphotic zone composites	10	5	>5	2-5	between ice out and freeze up
Oxygen	usually profile data	at distinct depths by Van Dorn or peristaltic pump (oxygen meter?)	sample frequency based on final use of data				key period just prior to fall de-stratification
Secchi	individual observations	Secchi disc	11-17 (weekly)	3-4 (monthly)	2-5	1	ice free period

* usually only enough time for 1 visit

Appendix 1: The Lakeshore Capacity Study Trophic Status Model for TP

The Ontario Trophic Status Model for TP is explained in detail in the final report of the Trophic Status component of the Lakeshore Capacity Study (Dillon *et al.* 1986).
Generally:

$$[TP]if = L\ (1-R_P)\ /\ 0.956q_s$$

where:

[TP] *if* = TP expressed as an ice-free mean

L = the total load of TP to the lake

$$L = (J_A + J_{PR} + J_N)\ /\ A_o$$

J_A = anthropogenic TP input
J_{PR} = TP input from precipitation
J_N = natural TP input from watershed
A_o = the area of the lake

R_p = the retention of TP by the lake

1. $Rp = 7.2\ /\ (7.2 + q_s)$ (anoxic hypolimnion)

2. $Rp = 12.4/(12.4+q_s)$ (oxic hypolimnion)

where 7.2 and 12.4 are the settling velocities and
q_s = the areal water loading rate (m/yr)

$$q_s = Q\ /\ A_o$$

where: Q = Annual lake outflow volume
Ao = Lake area

Appendix 1 continued

Equations for the conversion of TP values from one configuration to another:

ice-free vs. spring overturn	$[TP]_{if} = 0.80\ [TP]_{SO} + 2.04$
ice-free vs. fall overturn	$[TP]_{if} = 1.04\ [TP]_{fo} - 0.15$
ice-free vs. summer stratified	$[TP]_{if} = 1.04\ [TP]_{ss} - 0.33$
spring overturn vs. ice-free	$[TP]_{so} = 1.18\ [TP]_{if} - 1.19$
fall overturn vs. ice-free	$[TP]_{fo} = 0.88\ [TP]_{if} + 0.91$
summer stratified vs. ice-free	$[TP]_{ss} = 0.96\ [TP]_{if} + 0.33$
epilimnetic vs. ice-free	$[TP]_{epi} = 0.95\ [TP]_{if} - 1.23$
epilimnetic vs. summer stratified	$[TP]_{epi} = 0.98\ [TP]_{ss} - 1.44$

Appendix 2: The Molot Dillon Chlorophyll Model

The relationships between TP and Chl a for the set of Lakeshore Capacity Study lakes can be found in detail in:

Molot, L.A. and P.J. Dillon. 1991. Nitrogen/phosphorous ratios and the prediction of chlorophyll in phosphorous-limited lakes in central Ontario. Can. J. Fish. Aquat. Sci. 48:1 140-145.

and

Dillon, P.J., Molot, L.A., and R.A. Reid. 1991. Nitrogen/phosphorous ratios and the prediction of chlorophyll in phosphorous-limited lakes in central Ontario. OME report PIBS 1407.

Generally:

$$\mathrm{Chl}_{if} = 0.332\ \mathrm{TP} + 0.571$$

where TP is measured as a long term epilimnetic average. (TP_{epi})

Appendix 3: The Molot *et al.* Oxygen Model

Details of the Molot *et al.* oxygen model are outlined in:

> Molot, L.A., Dillon, P.J., Clark, B. and B.P. Neary. 1992. Predicting End-of-Summer Oxygen Profiles in Stratified Lakes, 1992. (Can. J. Fish. Aquat. Sci. in press).

Generally, the end-of-summer oxygen concentrations at each stratum (z) are determined by:

$$\log_{10} O_2(f)_z = 1.83 - 1.91/VSA_Z - 7.06/O_2\,(i)_Z - 0.0013\,TP^2_{SO}$$

where:
$O_2(f)$ = the end of summer oxygen concentration at depth 'z'
VSA = the volume - sediment surface area ratio at each 2 m stratum
$O_2(i)$ = the spring turnover oxygen concentration at depth 'z'
TP_{SO} = the spring turnover total phosphorous concentration

Spring turnover oxygen concentrations are measured directly or determined for each stratum (z) by:

(Where the maximum distance from shore to shore across the deepest portion of the lake is less than 1.4 km)

$$1og_{10}\, O_2(i) = 0.99 - 5.74/A_o + 0.64/z$$

or (Where the maximum distance (MD) from shore to shore across the deepest portion of the lake is greater than 1.4 km.)

$$1og_{10}\, O_2(i) = 1.07 - 6.95/A_o - 0.0043z/MD$$

A_o = the area of the lake in km^2.

Appendix 4: The Lakeshore Capacity Study water clarity (Secchi depth) model

The Lakeshore Capacity Model for Secchi disc depth is explained in detail in the final report of the Trophic Status component of the Lakeshore Capacity Study (Dillon *et al.* 1986).

Average ice-free Secchi depth is determined by:

$$SD_{IF} = -1.26\ DOC_{AN} - 0.065\ TP_{SO} - 0.039(\text{chl a})_{AN} + 10.27$$

or

$$SD_{IF} = -1.03 DOC_{AN} - 0.061\ TP_{SO} + 10.14$$

where: DOC_{AN} = measured average annual DOC
$(\text{chl a})_{AN}$ = average annual chlorophyll a
TP_{SO} = Spring overturn total phosphorous

Appendix 5: Equations used to estimate sample numbers.

Equations described in Green (1979, pg 41) were used to determine the number of samples required to be within 10 or 20 percent of the long term mean (with 95% confidence) Given:

$$\bar{X} * (\%/100) = 2\ SD / \sqrt{n}$$

where X = long term mean
$\%$ = percent difference from mean required
SD = standard deviation
n = number of samples

For estimating to within 10% of the mean and where '2' represents t at 95% the equation becomes:

$$\bar{X} * 0.10 = 2\ SD / \sqrt{n} \quad \text{or} \quad \bar{X} / 10 = 2\ SD / \sqrt{n}$$

Solving for n yields:

$$\sqrt{n} = (20\ SD / \bar{X}) \qquad \text{or} \quad n = (20\ SD / \bar{X})^2$$

Substituting coefficient of variance for SD/X yields:

$$n = (20 * cv)^2$$

The '20' in this equation can be replaced by '10' where numbers within 20% of the mean are required with a confidence of 95%.

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