ANALYSIS OF PHOSPHORUS AND ALGAL ABUNDANCE DATA FOR ST. MARY LAKE, BRITISH COLUMBIA

by

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Abstract

The data available in 2015 for total phosphorus concentration [TP], and for algal abundance, span the period 1974 to 2014. These data have been examined to determine their suitability for measuring changes in water quality over the past 40 years, and to calculate the change that would be required to be statistically significant. The conclusions are:

1) The total phosphorus (TP) data do provide a useful basis for examining changes with time of the amount of phosphorus in the epilimnion of the lake; however, the data measured in the hypolimnion are not considered useful for this purpose due to different locations and depths of measurement, and under-resolution of natural processes in time. Also, the algal abundance data do not provide a suitable metric for quantifying changes with time because of the low number of samples before 2000, inconsistencies in the data, changes in algal composition, and possibly differing analytical methods.

2) There has been *no significant change* in seasonally-averaged amounts of phosphorus in St. Mary Lake over the past 40 years, and by inference from the sediment core data, over the last 150 years. There are, however, large changes of the amount of P seasonally, and from year to year.

3) Average TP concentrations for all of the samples between 1974 and 2014, for years without aeration, are: spring 19 ± 7.3 μg/L, summer 17 ± 7.3 μg/L, fall overturn 51 ± 28.4 μg/L, based on the seasonal definitions used in this analysis (epilimnion only).

4) To be considered statistically significant, the 5-yr mean *change* in [TP] would have to exceed approximately 10 μg/L in both spring and summer, and by at least as much as 20 μg/L at the time of fall overturn, based on the definitions used in this analysis (epilimnion only).

5) Large increases in the epilimnion P mass have been measured at times that are *not* associated with fall turnover, and when external loading to the lake is nil or low. Sometimes these changes (> 500 kg) exceed the amount of P mixed throughout the water column at turnover. If such measurements are not in error, then an explanation for the source or mechanism for the increase is required.

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[1] This report was prepared by the author to document curiosity-driven research. The views expressed herein are those of the author and not of any other person or agency.

1.0 INTRODUCTION

Two data sets are considered in this report: in-lake measurements of phosphorus, and measurements of algal abundance obtained from water samples from the drinking water intakes for the NSSWD[2] treatment facility, and at mid-lake. These parameters have been measured over a long enough period to, perhaps, allow an assessment of the change in water quality over the past 40 years. No other parameters, with the possible exception of secchi depth, have sufficient sampling frequency to allow such an assessment. The focus in this paper is solely on these data and what they can, and cannot, tell us. No limnological or meteorological discussion is made other than to justify certain segmenting of the data for analysis.

In addition to looking at the change with time, a second question is examined: how much change would be needed over the next five or 10 years in order for it to be statistically significant. This may be relevant if steps are taken to reduce the phosphorus content of the lake and one wishes to determine if such actions are making a real difference, or not.

The data sets are described in Section 2, and the time-series parameters that can be derived from the phosphorus data to examine change with time, are defined in Section 3. The results are presented and discussed in Section 4 and the conclusions are summarized in the Section 5.

Watershed area	645 ha
Lake surface area:	182 ha
Lake volume	16,600 dam^3

Figure 1.1 Aerial photograph of St. Mary Lake.

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[2] North Salt Spring Waterworks District

2.0 DESCRIPTION OF THE DATA

2.1 Phosphorus

2.1.1 Definitions

Most phosphorus in surface water is present in the form of phosphates. There are four classifications of phosphates often referred to in environmental literature:

1. *orthophosphates* are the inorganic forms of phosphate, such as PO_4^{3-}, $HPO4^{2-}$, and $H_2PO_4^{-}$. These are the forms of phosphates used in fertilizers and are often introduced to surface waters through runoff. This is the form required by plants.
2. *organically bound phosphates* are found in plants, human and animal wastes or in decaying organic matter. They consist of a phosphate molecule associated with a carbon-based molecule, in plant or animal tissue.
3. *condensed phosphates (also called polyphosphates)*, such as $P_3O_{10}^{5-}$, are sometimes added to water supplies and industrial processes to prevent the formation of scaling and to inhibit corrosion. This form of phosphate was commonly found in detergents in the past.
4. *total phosphates* are the sum of all three of the forms described above. This is the most commonly reported form of phosphate concentration.

Orthophosphate concentration is determined by means of a chemical reaction resulting in a color change dependent upon the concentration of orthophosphates present. The intensity of the color is then measured with a colorimeter. The result of this laboratory test is often expressed as the *soluble reactive phosphate (SRP)* concentration.

The test for total phosphates involves digesting, or treating the sample with an acid and an oxidizer, and boiling to convert all the phosphates into orthophosphates. The orthophosphate test is then conducted on the sample. The results are reported as *total phosphates (TP)*.

The concentration of phosphate is expressed in units of milligrams/litre (mg/L) or micrograms/litre (μg/L). Only measurements of TP are considered here because they constitute the only P-dataset suitable for long-term analysis (sufficient number of samples distributed over time).

2.1.2 The NSSWD Dataset

These data were compiled by Bob Watson, former Trustee of the NSSWD, from different sources and are contained in an Excel workbook called *NSSWD-St Mary Lake-PhosDOTemp.xls*. This file was provided to the author by the District. The data consist of TP and span the time-period March 1979 to February 2013, with data gaps. The data density plots are shown in Fig. 2.1. The precision of the data is reported as 0.1 μg/L. Other parameters are included in the file – turbidity, dissolved oxygen, temperature – but these are not considered here. SRP is not included in this dataset.

Four depth ranges are represented in the header for the data: 0-2 m, 4-6 m, 8-11 m, and 12-15 m. The most likely sampling depths are 1, 5, 10 and 12 m. As far as I can tell, all of the data after 2005 were collected at a station called "mid lake south" (MLS), shown approximately in Fig. 2.2. Since the water depth at this location is a little over 12 m, the lowest sampling depth is taken as 12 m, despite the fact that

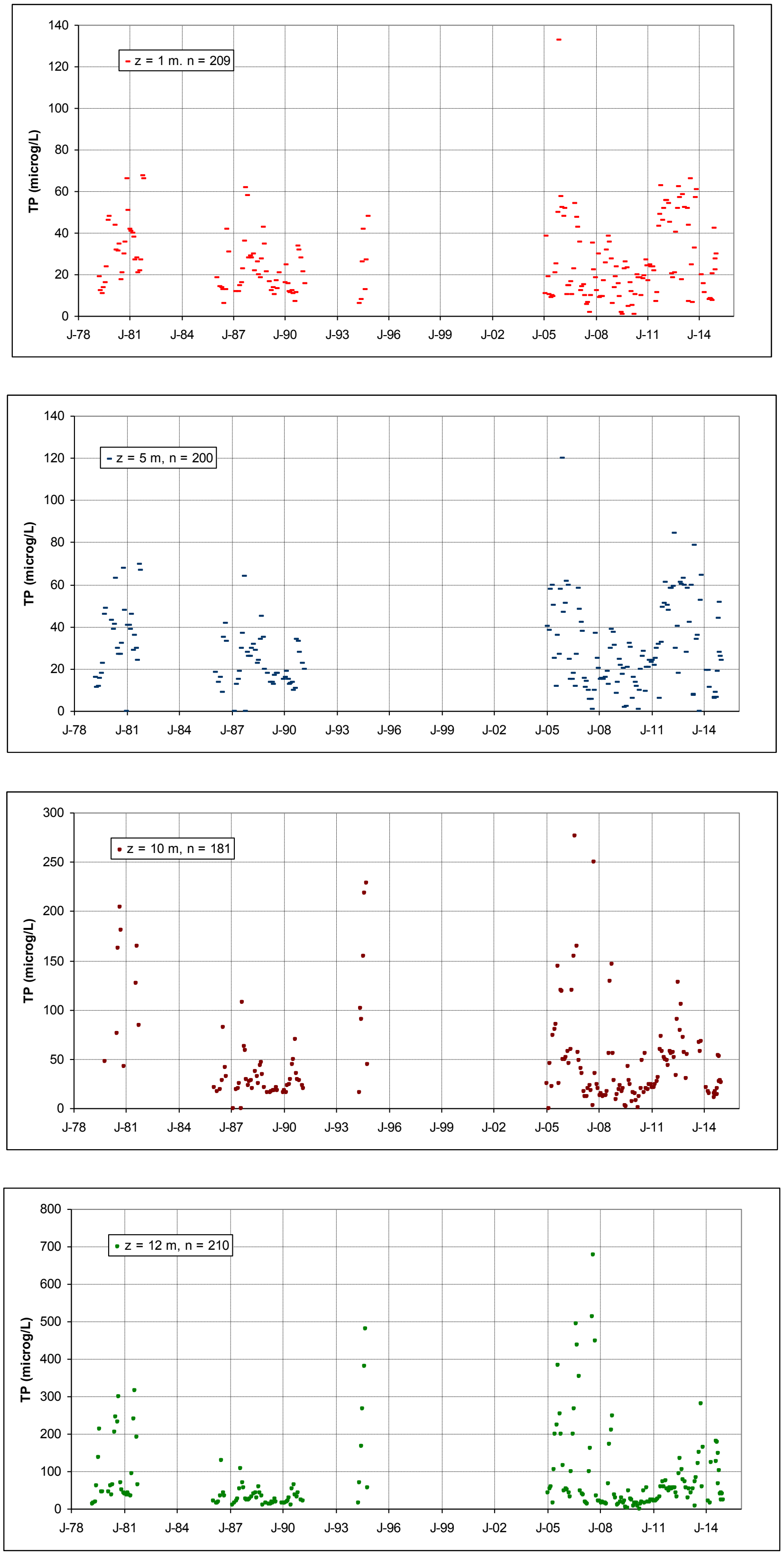

Figure 2.1 Data density plots for the NSSWD dataset. (source: *P-stock in lake history.xls*)

the stated range spans 12 to 15 m. Prior to 2005, the source of the data is unknown, as are the exact sampling depths. If the data were extracted from the Ministry of Environment file (see next section) then it is possible that the deepest samples were obtained below 12 m, since it is thought those data were collected from a location at a deeper part of the lake. Station co-ordinates were not available for either “mid lake south” or the MOE site.

The time stamp for the data does not contain a day, but only the month and year. Thus, in using these data one is forced to consider the sampling frequency to be “monthly” and I have taken the day to be at mid-month. Despite the imprecision of the time of sampling, the dataset has the advantage of being the longest available, particularly spanning the recent period 2005-2015 when data were not collected by the MOE.

Data were collected by the District and added to the file by the author after Bob Watson retired as Trustee. These additions extended the dataset to January 2015.

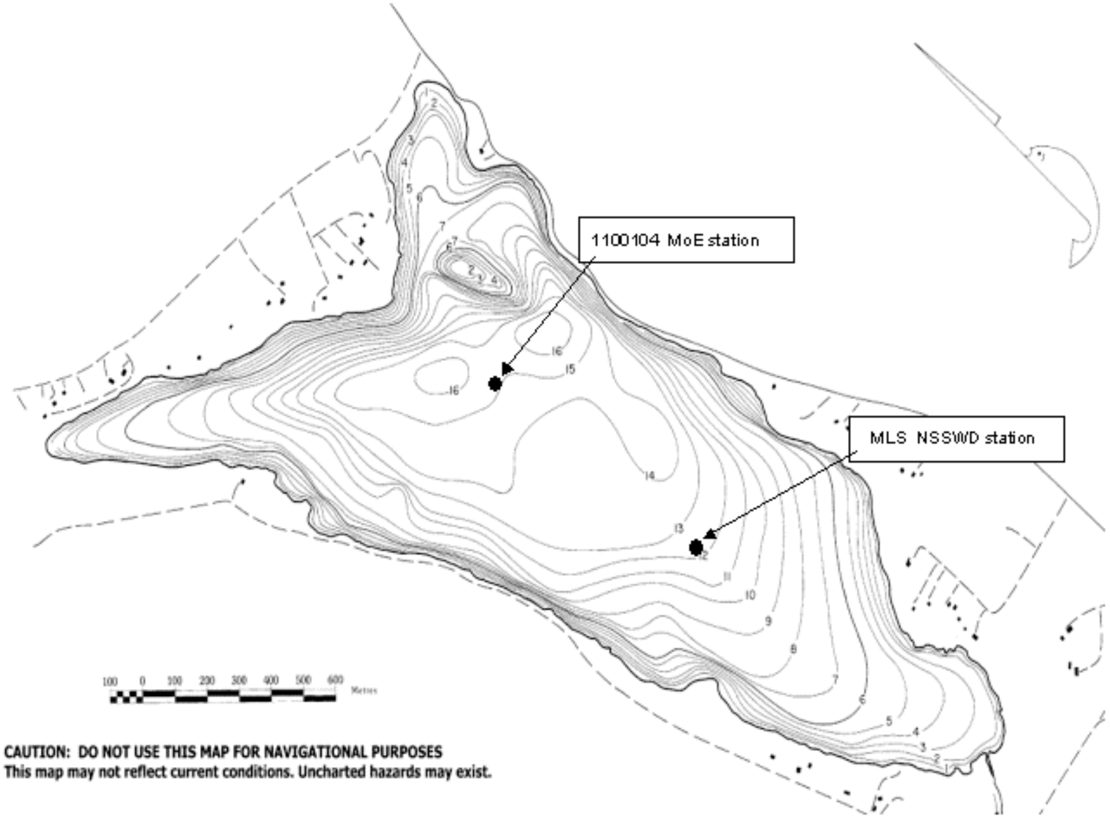

Figure 2.2 Approximate locations of sampling stations.

2.1.3 The MOE Dataset

This dataset is believed to be the MOE archive of all physical-chemical data collected in St. Mary Lake since inception of their program in 1974. The data are contained in the file *MOE - St Mary data to Oct 2007.xls,* which was provided to the author by NSSWD. Each record in the file contains a date-time stamp, sample depth, parameter name and units, parameter value and fields with reference to the analytical method. Many parameters are included in the file; however, only TP is examined here. The precision of reported values is 0.001 mg/L. The data density plots for TP are shown in Fig. 2.3. Based on the description provided in Nordin et al. (1983), pp. 7-8, the data were collected at site 1100104, shown approximately in Fig. 2.2.

The timing of sampling, as well as the depth of sampling, is not uniform over the dataset. For this reason the data density plots are shown for depth ranges that correspond, more or less, with the depths in the NSSWD dataset.

2.1.4 Comparison of the NSSWD and MOE Datasets

To make a comparison of the datasets, I have calculated the average of the TP measurements at 1 m and 5 m depth for both. This average provides a good measure of the epilimnion concentration, and these two time-series are plotted in Fig. 2.4. This shows that that the NSSWD series is comprised of the same data points as the MOE series, up to 2004[3]. For two years thereafter, additional sampling by NSSWD greatly augmented data collected by the Province and does not duplicate the measurements. Thus, it seems reasonable to conclude that prior to 2005 the two datasets are basically the same and I have treated the MOE data as one independent set. From 2005 onward, I have treated the NSSWD data as a second independent dataset.

Both data series are plotted chronologically in Fig. 2.5, together with the rainfall anomaly for the period September to the following February. The method of deriving the anomaly is described in Hodgins (2015a), but it is simply the amount of precipitation that exceeds or falls below the long-term mean signal. When the anomaly is positive, it is a wetter than average fall-winter, and vice versa. The significance of the Sep-Feb period is that it represents the major loading of phosphorus to the lake from storm water runoff and direct rainfall, and varies substantially from year to year. Thus, one might logically look for correlations between the anomaly and the overall TP concentrations in the lake.

While it might be tempting to relate the increase in TP in 1979 to the increase in rainfall after a particularly dry preceding year, this linkage does not repeat. In fact, high TP levels are not maintained through 1980-81 despite high rainfall, high TP levels occur in the late 1980s when rainfall was well below average, and wet winter of 2009-10 did not result in particularly high TP concentrations over winter.

Visually, then, it is apparent that the amount of fall-winter precipitation is not strongly correlated with the amount of phosphorus in the lake over winter. Other factors appear to be at least as important. Precipitation alone is not a reliable predictor of P-levels during the wet season.

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[3] There is also a difference between some of the values in each data set for 1993-1994. There is no obvious explanation available for why these points do not align, and may represent different data.

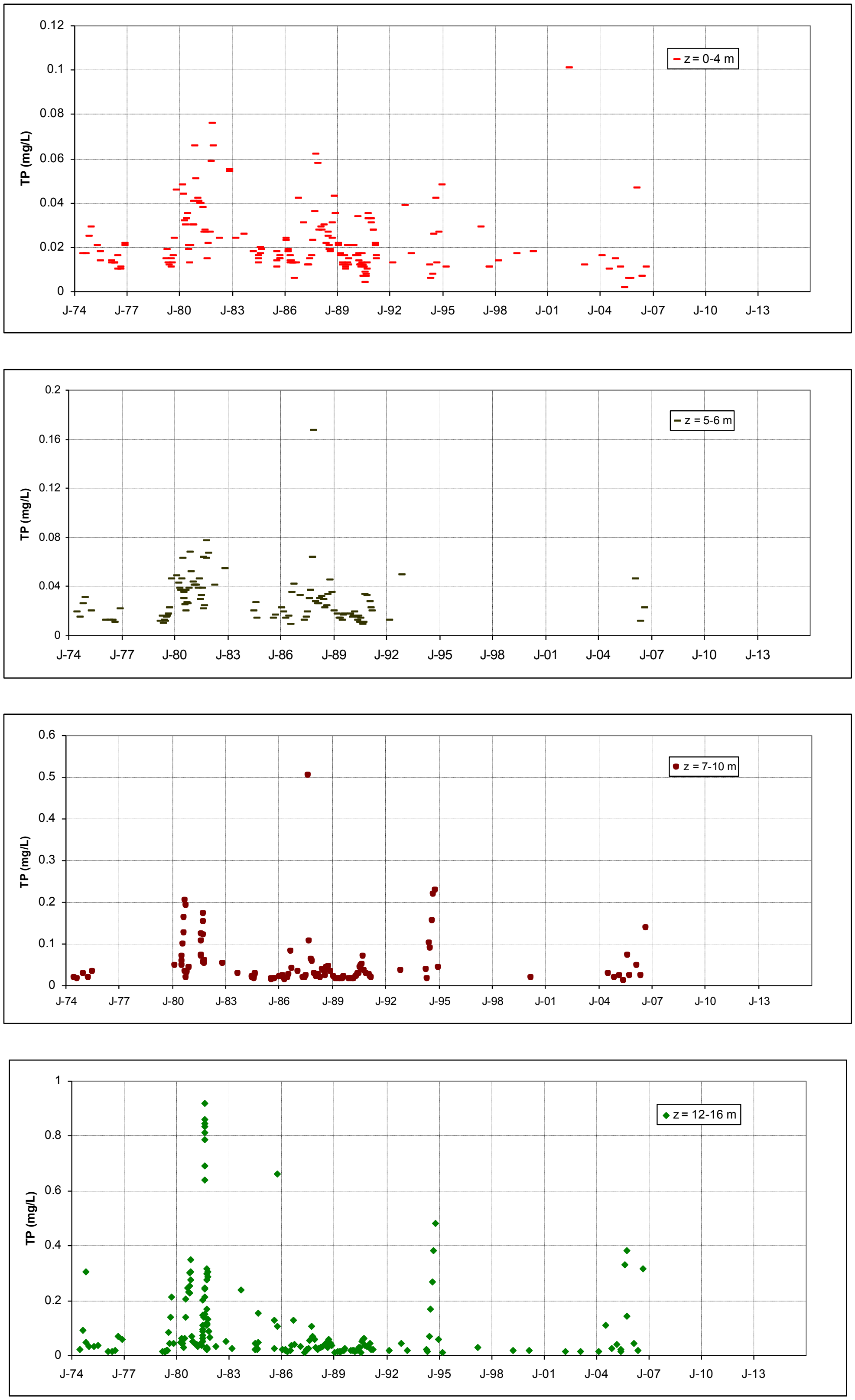

Figure 2.3 Data density plots for the MOE dataset. (source: *MOE - St Mary data to Oct 2007.xls*)

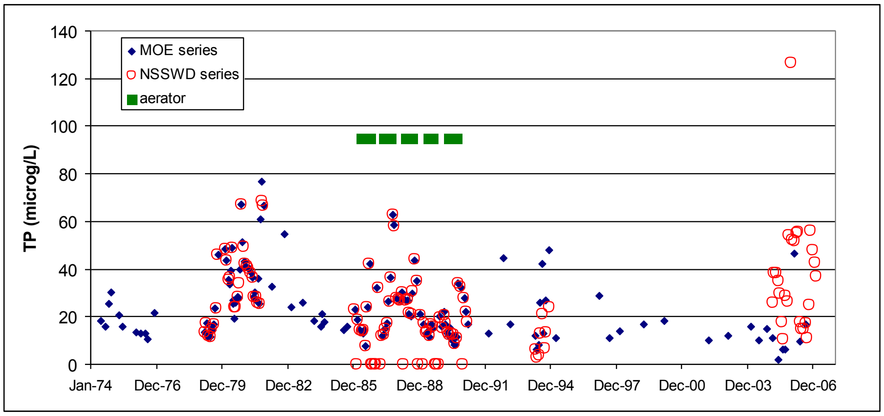

Figure 2.4 Comparison of the MOE and NSSWD datasets based on the average [TP] at 1 m and 5 m. Notes: (i) the red circles with zero values on the x-axis are a plotting artefact from data gaps in the epilimnion record and not valid observations. (ii) aeration also took place from 1991-1993, although no measurements were made during the periods of aeration, and thus no green bars are plotted to indicate their operation.

2.3 Algal Abundance

2.3.1 The NSSWD Dataset

Data on algal abundance were obtained from the drinking water intakes, which withdraw lake water from approximately 5 and 7 m depth. Samples were taken when turbidity exceeded about 2 to 3 NTU, or problems with clogging the sand filters were detected. Otherwise, no sampling was carried out, and as a result the data are irregular in time and contain gaps. The data record begins in 2003.

The data, which were compiled by Bob Watson and provided to the author by the District (*mm-cyanobacterial-toxins-and-algae-st-mary-lake.xls*), consist of abundance counts for seven cyanobacteria species (Anabaena, Anacystis, Aphanizomenon, Cylindrospermum, Lyngbya, Nodularia, Oscillatoria) and total algae in units of cells/mL. The data density plot for total algae is shown in Fig. 2.6.

2.3.2 The MOE Dataset

Data on algal abundance were also collected by the MOE, beginning in 1974-75 (4 samples) and repeated in 1979-1981 (34 samples). These data were available to the author in hardcopy form from the Nordin et al. (1983) report, and are reproduced in Appendix A; only the total cell counts were transcribed into spreadsheet format for analysis (Fig. 2.6). The depth of sampling was reported as “surface” in the Nordin et al. report. The sampling frequency was, approximately, monthly or slightly more often in some seasons.

2.3.3 Discussion of Algal Datasets

Compared with the NSSWD dataset, the number of samples in the MOE dataset is small, and this makes a statistical comparison imprecise. More importantly, however, during the plankton bloom of 1979-81, the highest total cell counts are more than one order of magnitude (10 times) greater than for all later data in the NSSWD dataset. Reasons for this difference may include: (i) different sampling depths – surface for MOE vs 5 to 8 m for NSSWD, (ii) different locations of sampling, (iii) differences in species composition, and, possibly, (iv) differences in enumeration methods. It is understood that algal abundance varies significantly with depth, and with time of day, and thus it is conceivable that the surface samples would

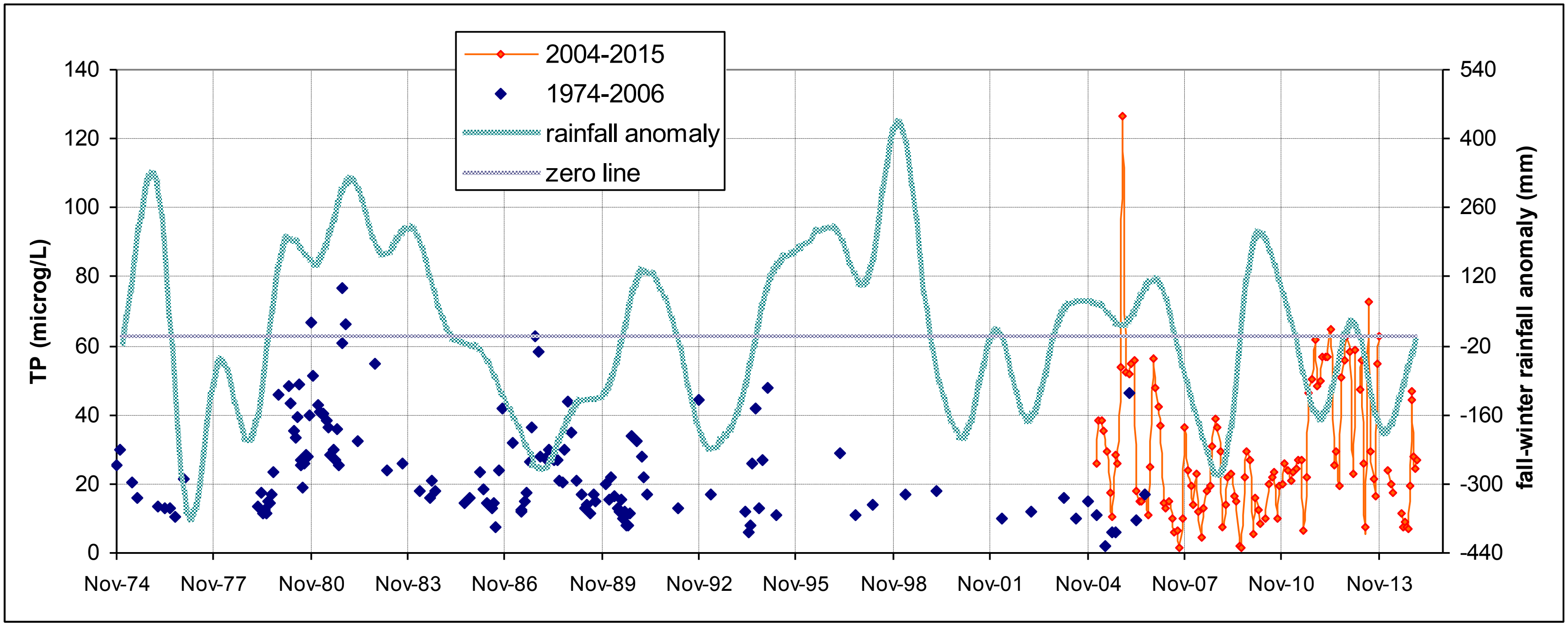

Figure 2.5 Time-series of epilimnion [TP] data, both sources, and fall-winter rainfall anomaly.

contain greater amounts of algae than in samples extracted near and in the thermocline. There is support for this argument in the chlorophyll data collected by MOE, which is typically greatest near the surface except for the hot summer months of July and August (Nordin et al. 1983 report p.88). Both the 1979-81 and the 2011-13 blooms were dominated by cyanobacteria (typically greater than 90% of the total count). However, the dominant cyanobacteria species through 1980-81 was identified as Oscillatoria at times of greatest abundance. The 2011-13 bloom was also dominated by cyanobacteria, in this case Aphanizomenon with lower counts of companions Anabaena and Anacystis. Although I have been advised (Wendy Riggs[4], MB Laboratories Ltd., pers. comm., 2015) that these differences in species composition should not, in themselves, explain the order-of-magnitude difference in total count, there are sufficient reasons (spatial separation, sampling and enumeration methods) to suspect that these two datasets are not statistically equivalent. Therefore, I have not pursued this analysis further, and conclude that the available algal abundance data are not suitable for determining differences with time.

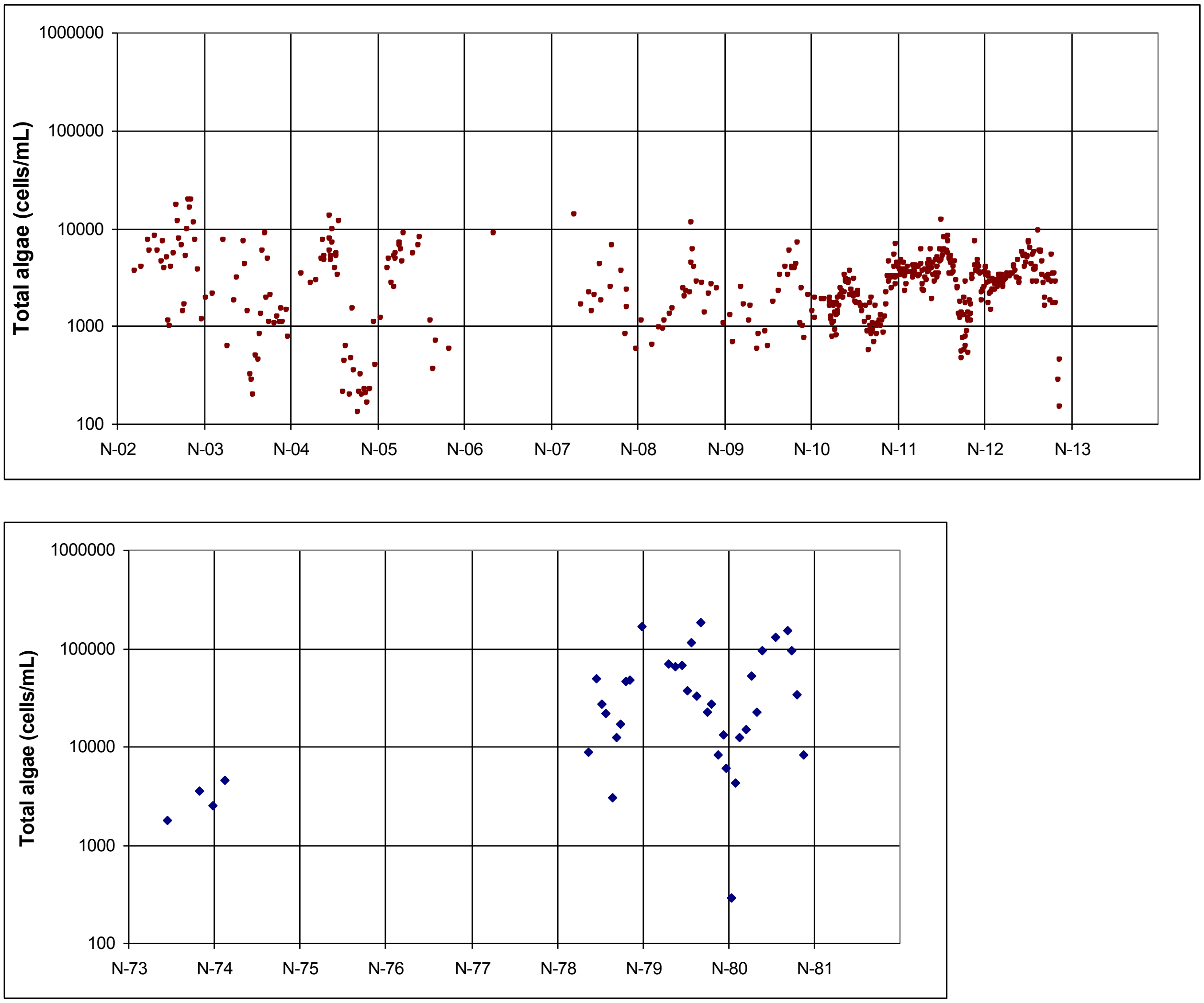

Figure 2.6 Data density plots for total algal abundance. NSSWD dataset (upper panel), MOE dataset (lower panel).

3.0 DERIVED TIME-SERIES AND DISCUSSION

It is well understood that the TP signal exhibits seasonal variation; less clear is whether, or not there is a persistent inter-annual (low frequency) signal and what would cause it. The seasonal signal results from varying gains and losses of P from runoff, precipitation, export by Duck Creek and withdrawals, sedimentation and the release of P from sediments during anoxia and subsequent mixing at the time of fall overturn. Accordingly, a meaningful comparison of P-levels, and their change with time, requires partitioning of the original time-series {TP}[5] into equivalent populations at different times of the year; that is, equivalent in the sense that the balance of sources and sinks is roughly the same for each set of samples. This is certainly not perfect: the TP concentration at a selected time depends on how much is carried over from prior months, and that amount varies from year to year. However, let us see what the data shows.

In the following analysis, three derived time-series are considered:

1) *spring* defined as the min{TP} during March, April or May. The minimum value is selected because the timing of the end of the wet season runoff and the export of P out Duck Creek while the weir is overflowing, varies considerably from year to year. Using the minimum value attempts to minimize the influence of these variations on the sample set, and provides a variable indicative of conditions prior to the onset of stratification effects on the vertical variation of TP. Inspection of the results indicates that this method is better (smaller variance) than selecting a single month, e.g., March.

2) *summer* defined as the average {TP} concentration for July and August. Inspection of the data shows that these values tend to be similar, and amongst the lowest of the year during a period when external loads to the lake are very low or negligible. This series also affords comparison with the sediment core estimates of summer TP spanning the past 150 years.

3) *overturn* defined as the max{TP} during October, November or December. This series attempts to isolate the largest value associated with mixing of P released from sediments after turnover in the fall. However, for reasons discussed further below, this series is problematic and is of limited use.

All of the derived time-series pertain to the epilimnion. The principal reason for excluding the hypolimnion is the lack of consistent resolution of the depth-wise variations in TP, which are known to be large, certainly from the intensive monitored completed in 2014. Such inconsistent resolution, and the possible depth limitation (< 13 m or so) of the NSSWD dataset after 2005, introduces too much variability into any time-series that can be derived to be useful in the context of change detection.

Aerators. A further partitioning of the data must be considered because of the influence of the aerators. It has been established using data collected by Bob Watson that aerator operation results in a sharpening of the thermocline, and warming of the lower layer, produced by mechanical mixing. Under conditions of anoxia[6], mixing also has a possible influence on the distribution of P released from bottom sediments, increasing the P-gradient across the sediment-water interface, as well as at the thermocline. The first enhances diffusion of P from sediments; the latter conceivably leads to an increase of P-diffusion across

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[5] The symbol {..} denotes a time-series of discrete values.

[6] This may occur when the oxygen transferred from aerators is insufficient to meet the oxygen depletion rate in deeper waters of the lake. Such conditions did occur in St. Mary Lake in 2012 and 2013, during periods when the aerators were in operation.

the thermocline, modifying the epilimnion TP levels in a manner that does not occur without aerator operation. Thus, partitioning the data into aerator and non-aerator years is examined in the following analysis.

Time blocks. To facilitate an analysis of change in P levels, the data are divided into two time blocks, each of which is further separated into two blocks that exclude the aerator years, as follows:

1. 1974 to 2006 aeration effects ignored
2. 1974 to 2006
    a) 1974 to 1985, 1994 to 2006 no aeration
    b) 1986 to 1994, aeration (note the spring data following an overturn data point are included in the aeration block)
3. 2005 to 2014 aeration effects ignored
4. 2005 to 2014
    a) 2005 to 2009, 2014 (summer, fall) , no aeration
    b) 2009 to 2014 (spring), aeration (discontinued August 2013)

It is recognized that the two main blocks overlap in time by two years. One could easily discard the post-1994 data from the early block; however, there are only a few data points involved, particularly for the summer and overturn data, and they have been retained.

The data series for blocks 1 and 3 are plotted in Appendix B to illustrate their relationship to the total dataset in each period.

4.0 RESULTS - PHOSPHORUS

4.1 Change with Time

The derived data are listed chronologically in Table 4.1, and partitioned into aerator and non-aerator years in Table 4.2. These same data, rank ordered, are also plotted in Fig. 4.1. These graphs provide easy visual comparison of the relative magnitude of the data points, and show that differences are typically small except for the largest value in each season. Summary statistics are listed in Table 4.3.

Inspection of Table 4.3 shows, for all data in each block, that the standard deviation is relatively large compared with the mean, and that there is a substantial difference in this ratio between the first dataset and the second. Specifically, for the 1974-2006 dataset, s_1/μ_1 ranges from 39% to 43%; in the second dataset, from 2005-2015, s_2/μ_2 ranges from 53% to 77%. Indeed, the character of the two time-series appears to be different (Fig. 2.5) with the later dataset noisier. In these circumstances, the appropriate two-sample means test is one that accounts for unequal variances (see e.g., Moser and Stevens, 1992; and a quite good explanation of the rationale behind this method in Ruxton, 2006).

Let μ_1 and μ_2 equal the means of two samples $\{x_1\}$ and $\{x_2\}$ with elements n_1 and n_2 and standard deviations s_1 and s_2. The test statistic is:

$$t' = (\mu_2 - \mu_1)/\sqrt{(s_1^2/n_1 + s_2^2/n_2)} \qquad (1)$$

The number of degrees of freedom ν is equal to:

$$\nu = (1/n_1 + u/n_2)^2/[\ 1/(n_1^2(n_1-1)) + u^2/(n_2^2(n_2-1))\ ] \qquad (2)$$

where $u = s_2^2/s_1^2$. Table 4.4 provides the results of evaluating (1) and (2) for the case of all data (blocks 1 and 3) and for data without aeration (blocks 2a and 4a).

In both cases, for all seasons, $t' <$ test statistic at 5% level of significance (α 5%) and we can conclude that there is *no significant difference* between the mean values.

As noted previously, the overturn data are problematic. The timing of the fall maxima varies from year to year, and. the duration of peak concentrations at that time is poorly understood. Bi-weekly data collected in 2014 suggests that these durations may be only days to a few weeks before the phosphorus binds with iron and settles out of the water column. As a result, even monthly sampling will under-resolve the signal and potentially introduce variance into the sample set that is not due to natural processes. In the earlier dataset, monthly sampling took place only through 1980-81 and 1987-90, and so the problem is potentially worse then compared with the later dataset, because it includes data with less than monthly sampling frequency.

The 2005-2014 overturn dataset contains one very high value (126 μg/L December 2005), which may be an error. The [TP] recorded at all four depths for that time was essentially the same, indicating that the lake had mixed. However, in November 2005, the lake was still stratified with epilimnion concentrations of ~ 55 μg/L and lower layer concentrations of 120 and 200 μg/L. The total phosphorus mass in November was thus, approximately, 1340 kg. One month later it has increased to over 2000 kg, representing a one-month addition of about 700 kg. Although there was ~200 mm of rain in November, and the first half of December, runoff would not likely account for the addition of 700 kg. Runoff loads are typically about 20-30 kg/mo at that time of year (Hodgins, 2015b). Consequently, the high December-2005 value looks suspicious, but cannot absolutely be ruled out. Obviously, retaining this value increases the mean, and the variance. Removing the Dec 2005 value changes the mean to 46.8 μg/L (n = 9), which for all practical purposes equals the 1974-2005 average value of 44.4 μg/L.

Another concern arises during the fall samples for 2011-2013 in that the lake was experiencing an unusually long-lasting algal bloom (elevated but highly variable [TP] shown in Fig. 2.4). The presence of algae in such high numbers is not representative of "normal" conditions and clearly gives rise to three large P sample values (~ 63 μg/L) in a total of n = 10. As with the single large 2005 value, these raise the mean, which in turn results in a larger change from earlier conditions than might otherwise be expected. For these reasons, the overturn results are given less credence than the spring and summer results.

The results for the years when aeration was effective (Table 4.3, blocks 2b and 4b) show that the differences in the means are similar in magnitude to those for all data combined (blocks 1 and 3), and for effective aeration (blocks 2a and 4a). I did not compute t-test statistics for blocks 2b and 4b because the number of observations is too small; however, inspection of the spring data, for example, shows that all of these data span the same range (Fig. 4.2). The conclusion is that for years when aeration was effective in keeping the hypolimnion oxygenated, there is no measurable difference between the 1980s and 2009-2010.

4.2 Comparison with Sediment Core Data

Cumming et al. (2006) describe the analysis of a 10-cm sediment core, obtained from St. Mary Lake in 2002, for diatom assemblages and inferred mid-summer TP concentrations at different times over the preceding 150 yr. One conclusion reached by those investigators was that summer TP concentrations have been relatively constant for the past 150 yr with values ranging from 13 to 16 μg/L. The authors provide no estimate of confidence limits for the inferred [TP]. By way of comparison, the summer averages, pre- and post-2005, are 18 ± 7.4 and 13 ± 5.2 μg/L (without aeration). Given the variability in the TP observations, it is reasonable to conclude that there has been no significant change over the past 40 years, and most likely, over the past 150 years.

4.3 Change Detection

The results from the tests in Table 4.4 provide a means of estimating how much change in TP would be required at, say, the 5% level of significance to be considered real. One might ask this question if, for example, one attempted to lower phosphorus levels through reducing external inputs, or some other means. If the variance characteristics of, say, a future 5-year monitoring program were to remain the same as over the past 5 – 10 years, then the *minimum* differences in the means would have to be:

$$(\mu_2 - \mu_1) = \alpha(5\%) \times \surd(s_1^2/n_1 + s_2^2/n_2) \qquad (3)$$

The results from (3) are given in Table 4.4 without changing the number of observations. What they show is that for spring and summer, a change of *at least* 8 to 10 μg/L would be required. At overturn, the minimum change would have to exceed, at the very least, 20 μg/L, but probably more. It is difficult to pin that last number down more precisely because of the large variance in the observed datasets and the uncertainties described previously.

Table 4.1 TP data series in chronological order.

spring	**µg/L**	**summer**	**µg/L**	**Overturn**	**µg/L**	**spring**	**µg/L**	**summer**	**µg/L**	**Overturn**	**µg/L**
Jun-74	18	Aug-74	16	Dec-74	31	May-05	35.2	Jul-05	14.1	Dec-05	126.5
Apr-75	21	Aug-76	11	Nov-76	22	May-06	17.7	Jul-06	16.2	Nov-06	56.3
Apr-76	13	Jul-79	18	Oct-79	46	Apr-07	13.0	Jul-07	6.1	Nov-07	36.3
Mar-79	12	Jul-80	25	Nov-80	68	Apr-08	12.0	Jul-08	18.6	Oct-08	38.9
Mar-80	34	Jul-81	30	Oct-81	77	May-09	16.5	Jul-09	1.8	Oct-09	29.2
Mar-81	29	Sep-83	26	Nov-82	55	Mar-10	8.6	Jul-10	22.8	Dec-10	25.7
Apr-82	33	Jul-84	18	Nov-87	64	Mar-11	23.3	Jul-11	14.2	Nov-11	62.0
Mar-83	24	Jul-85	15	Oct-88	45	Mar-12	57.0	Jul-12	24.4	Nov-12	62.7
Mar-84	18	Jul-86	16	Dec-89	21	May-13	26.0	Jul-13	51.0	Nov-13	62.9
Mar-86	13	Jul-87	22	Oct-90	35	Apr-14	17.6	Jul-14	8.7	Nov-14	46.9
Apr-87	12	Jul-88	21	Nov-92	50						
Mar-88	27	Jul-89	16	Dec-94	48						
Mar-89	11	Jul-90	9	Nov-04	15						
Mar-90	10	Jul-94	27								
Mar-91	17	Jul-04	10								
Mar-92	13	Aug-05	6								
Mar-93	17	Aug-06	17								
Apr-94	6										
Mar-95	11										
Mar-97	29										
Mar-98	14										
Mar-99	17										
Mar-00	18										
Mar-02	10										
	spring		summer		overturn		spring		summer		overturn
count	24		17		13		10		10		10
stdev	7.6		6.7		19.0		14.3		13.6		28.8
mean	17.7		17.8		44.4		22.7		17.8		54.7
max	34		30		77		57		51		127
min	6		6		15		9		2		26
🟩	- potentially influenced by hypolimnetic aeration										

Table 4.2 TP data series separated by periods with and without aeration.

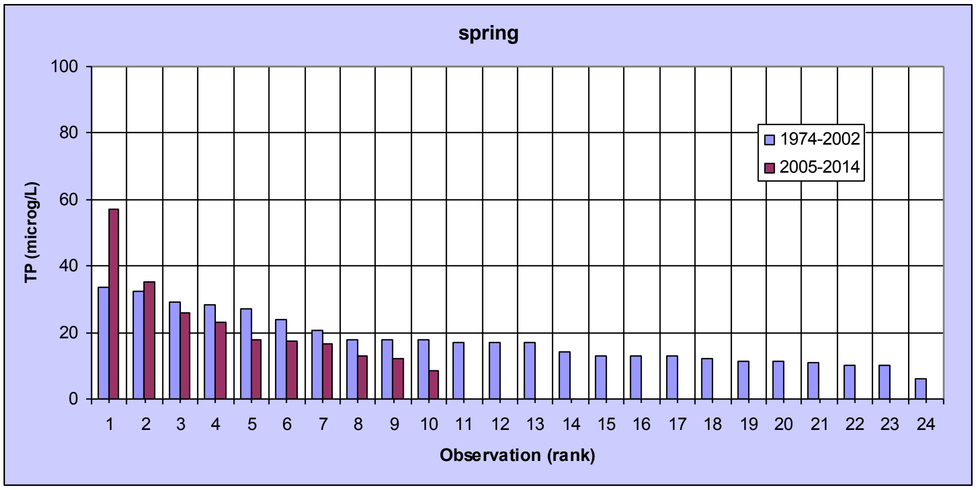
spring	**µg/L**	**summer**	**µg/L**	**Overturn**	**µg/L**	**Spring**	**µg/L**	**Summer**	**µg/L**	**overturn**	**µg/L**
Jun-74	18	Aug-74	16	Dec-74	31	May-05	35.2	Jul-05	14.1	Dec-05	126.5
Apr-75	21	Aug-76	11	Nov-76	22	May-06	17.7	Jul-06	16.2	Nov-06	56.3
Apr-76	13	Jul-79	18	Oct-79	46	Apr-07	13.0	Jul-07	6.1	Nov-07	36.3
Mar-79	12	Jul-80	25	Nov-80	68	Apr-08	12.0	Jul-08	18.6	Oct-08	38.9
Mar-80	34	Jul-81	30	Oct-81	77	May-09	16.5	Jul-14	8.7	Nov-14	46.9
Mar-81	29	Sep-83	26	Nov-82	55	Apr-14	17.6				
Apr-82	33	Jul-84	18	Dec-94	48						
Mar-83	24	Jul-85	15	Nov-04	15						
Mar-84	18	Jul-94	27								
Mar-86	13	Jul-04	10								
Mar-95	11	Aug-05	6								
Mar-97	29	Aug-06	17								
Mar-98	14										
Mar-99	17										
Mar-00	18										
Mar-02	10										
		Jul-88	21	Nov-87	64			Jul-09	1.8	Oct-09	29.2
Mar-89	11	Jul-89	16	Oct-88	45	Mar-10	8.6	Jul-10	22.8	Dec-10	25.7
Mar-90	10	Jul-90	9	Dec-89	21	Mar-11	23.3	Jul-11	14.2	Nov-11	62.0
Mar-91	17			Oct-90	35	Mar-12	57.0	Jul-12	24.4	Nov-12	62.7
Mar-92	13			Nov-92	50	May-13	26.0	Jul-13	51.0	Nov-13	62.9
Mar-93	17										
Apr-94	6										
	spring		summer		overturn		spring		summer		overturn
count	16		12		8		6		5		5
stdev	7.8		7.4		21.7		8.4		5.2		37.5
mean	19.5		18.2		45.3		18.7		12.7		61.0
max	34		30		77		35.2		18.6		126.5
min	10		6		15		12.0		6.1		36.3
count	6		3		4		2		3		2
stdev	4.3		5.7		12.8		10.4		10.6		2.5
mean	12.4		15.3		37.8		15.9		12.9		27.5
max	17		21		50		23.3		22.8		29.2
min	6		9		21		8.6		1.8		25.7
🟩	- samples when aeration effective					🟧	- samples when aeration failed				

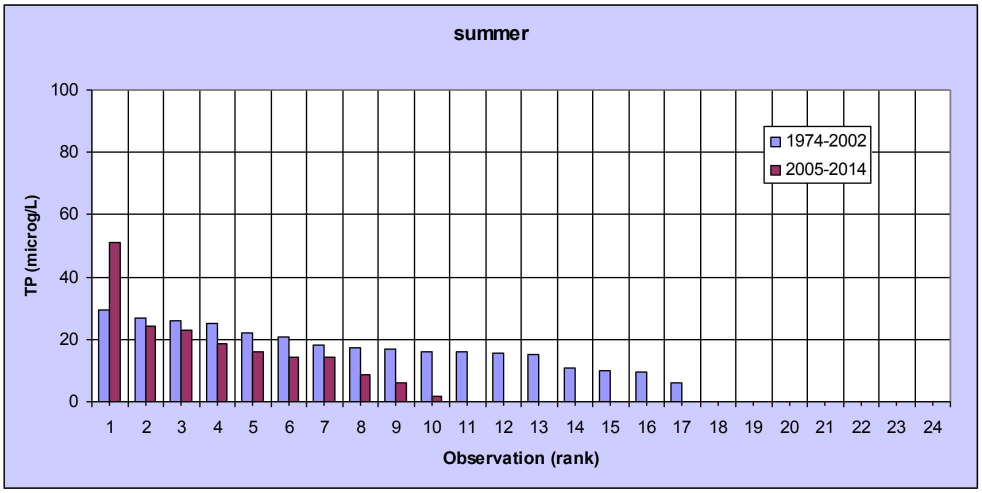
Table 4.3 Summary statistics.

		1974-2006			**2005-2015**			**difference**		
		spring	**summer**	**overturn**	**spring**	**summer**	**overturn**	**spring**	**summer**	**overturn**
		all data								
observations	n	24	17	13	10	10	10			
standard dev.	s	7.6	6.9	19.0	14.3	13.6	28.8			
mean	μ	17.7	17.8	44.4	22.7	17.8	54.7	5.0	-0.03	10.3
max		34	30	77	57.0	51.0	126.5			
min		6	6	15	8.6	1.8	25.7			
	s/μ	43%	39%	43%	63%	77%	53%			
		data without aeration								
Observations	n	16	12	8	6	5	5			
standard dev.	s	7.8	7.4	21.7	8.4	5.2	37.5			
mean	μ	19.5	18.2	45.3	18.7	12.7	61.0	-0.8	-5.46	15.7
max		34	30	77	35.2	18.6	126.5			
min		10	6	15	12.0	6.1	36.3			
		data with effective aeration								
observations	n	6	3	4	2	3	2			
standard dev.	s	4.3	5.7	12.8	10.4	10.6	2.5			
mean	μ	12.4	15.3	37.8	15.9	12.9	27.5	3.5	-2.41	-10.3
max		17	21	50	23.3	22.8	29.2			
min		6	9	21	8.6	1.8	25.7			
Concentration units are microg/L										

Table 4.4 Comparison of means and variances.

		1974-2006			2005-2015			difference		
		spring	summer	overturn	spring	summer	overturn	spring	summer	overturn
All data										
	s1^2	58.2	47.6	362.1						
	s2^2				204.0	186.3	831.6			
	u				3.504	3.915	2.297			
deg freedom	ν				11	11	14			
	sd				4.777	4.629	10.536			
	t'				1.041	na	0.981			
	α(5%)				2.201	2.201	2.145			
	change							**11**	**10**	**23**
No aeration										
	s1^2	60.7	55.2	469.6						
	s2^2				71.0	27.0	1403.4			
	u				1.170	0.490	2.988			
deg freedom	ν				8	10	5			
	sd				3.952	3.164	18.422			
	t'				na	na	0.853			
	α(5%)				2.306	2.228	2.571			
	change							**9**	**7**	**47**





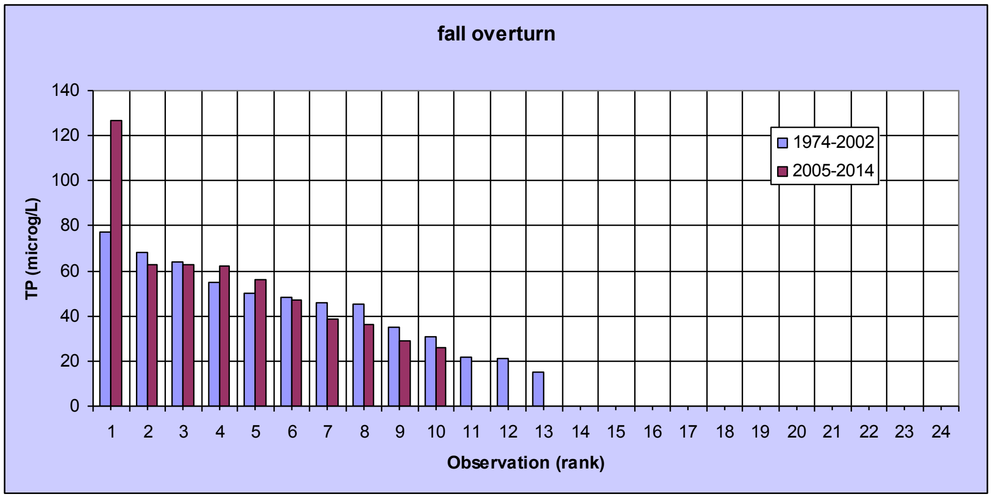


Figure 4.1 Comparison of derived sample sets for each time period. The data are shown in rank-ordered form, from largest to smallest. The number of bars differs because the sets contained unequal numbers of observations.

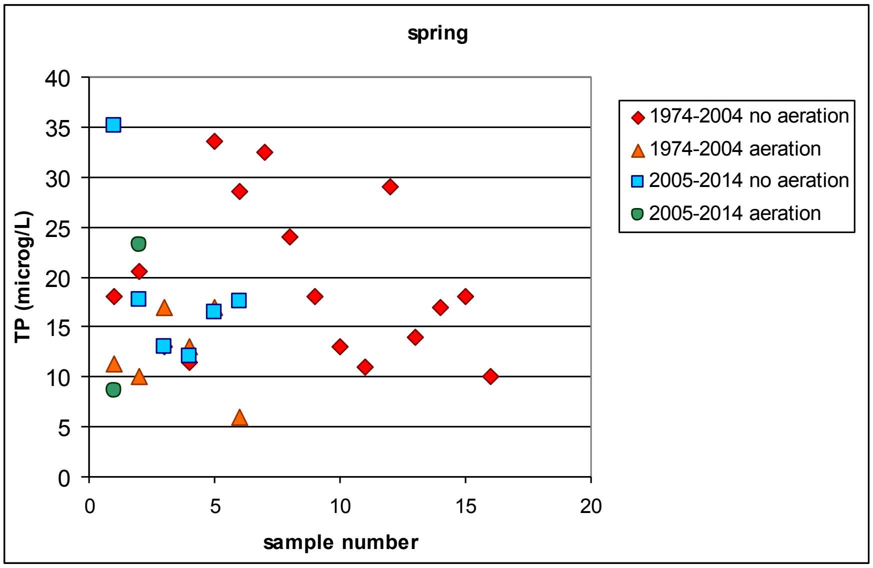


Figure 4.2 Comparison of spring samples with and without effective aeration of the hypolimnion.

4.4 Question Arising: Is TP Conservative?

As noted in the definitions, [TP] is supposed to measure all forms of phosphorus in the sample. If we assume that condensed phosphates are not present, or are at negligibly low concentrations, then [TP] represents the sum of the amounts of organically-bound P and PO4-P present at any given time. If the organically-bound P is associated primarily with the algae present in the pelagic portion of the lake (since that is the location of the measurements), then the balance exists as SRP. The relative amounts of each may change, but the total should remain constant if sources and sinks are zero (i.e., TP is a conservative property).

It is assumed that as algae die, they sink out of the epilimnion carrying some organic-P with them. This represents a removal mechanism that can reduce the amount of TP measured in the upper layer without altering the amount of SRP.[7] So, from sample to sample one may expect to see decreases in [TP], sometimes substantial when a bloom collapses. On the other hand, one would not expect large, rapid increases in TP except at the time of fall overturn when the lake mixes.

Figure 5.1 illustrates the forward first difference, ΔP, defined as:

$$\Delta P^{n} = (TP^{n} - TP^{n-1}) \times 12.08^{8} \qquad (1)$$

where n = monthly time index. For clarity, the graph shows only $\Delta P > 100$ kg. When the red bars coincide with the November gridlines, or within a month either way, then the additions can be explained by the overturn and mixing of high-P water from the hypolimnion throughout the water column. Typical numbers range from about 300 to 500 kg when this overturn mixing occurs.

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[7] It is recognized that bacterial decomposition of dead algal cells releases SRP back into solution and that this can take place above the thermocline. However, without sinking and external sources and sinks, [TP] should remain constant.

[8] If [TP] is expressed in μg/L and the volume of the epilimnion is taken as 12,080,000 m^3, then the factor 12.08 times the concentration yields the mass of P in kg. The conversion factors for mass and volume cancel out.

The question arises for the red bars situated in between the overturn bars: in the years 2008, 2010 and 2011 large additions to the upper layer occurred during summer or early fall months. In particular, in 2011, over 500 kg of P was added to the upper layer in August and September, a period of stable stratification and virtually no external load. At least, according to the data in the NSSWD file. Again, in 2013, large increases in P were observed in February, May and July, in two cases exceeding 450 kg. This situation is not unique to the NSSWD data. Monthly increases during spring and summer occurred in 1980, 1986 and 1987 with values ranging from about 150 to over 400 kg. There may have been other occurrences in those early years, but the data are not sufficient to identify them.

A quantitative explanation for the appearance of such large quantities of P in the upper layer of the lake is required, since external loading appears unlikely to provide a viable source. That is, if TP is a conservative property.

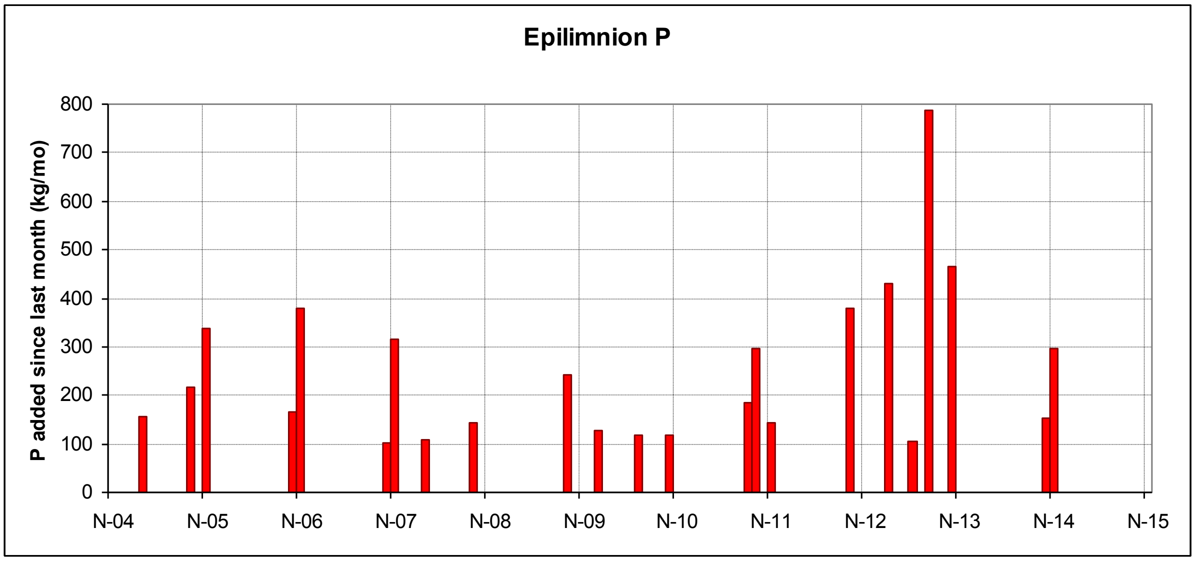


Figure 5.1 Change in P from last month to this month (ΔP). Be careful reading this graph: it *does not* show how much P is in the lake; it does show how much was added from the month before.

5.0 CONCLUSIONS

The data available in 2015 for total phosphorus concentration [TP], and for algal abundance, span the period 1974 to 2014. A review of their statistical properties provides the following conclusions:

6) The [TP] data do provide a useful basis for examining changes in the amount of phosphorus in the epilimnion of the lake over the past 40 years. For various reasons – low number of samples, different depths and locations of sampling, inconsistencies, changes in algal composition, differing analytical methods – the algal abundance data do not.

7) The [TP] data measured in the hypolimnion are not considered useful for measuring the long-term change in P levels due to changes in location and depth of measurement, and under-resolution of natural process in time.

8) Average TP concentrations for all of the samples between 1974 and 2014, for years without aeration, are: spring 19 ± 7.3 μg/L, summer 17 ± 7.3 μg/L, fall overturn 51 ± 28.4 μg/L, based on the seasonal definitions used in this analysis (epilimnion only).

9) There has been *no significant change* in seasonally-averaged amounts of phosphorus in St. Mary Lake over the past 40 years, and by inference from the sediment core data, over the last 150 years. There are, however, large changes of the amount of P seasonally, and from year to year.

10) To be considered statistically significant, the 5-yr averaged *change* in [TP] would have to exceed approximately 8 to 10 μg/L in both spring and summer, and as much as 20 μg/L at the time of fall overturn, based on the definitions used in this analysis (epilimnion only).

11) Large increases in the epilimnion P mass have been measured at times that are *not* associated with fall turnover, and when external loading to the lake is nil or low. Sometimes these changes (> 500 kg) exceed the amount of P mixed throughout the water column at turnover. If such measurements are not in error, then an explanation for the source or mechanism for the increase is required.

Acknowledgements

Data used in this study were provided by the North Salt Spring Waterworks District, with support from Ms. Meghan McKee, the Water Quality Specialist with the District. I also received valuable review comments from Dale Green, CRD, and Shannon Cowan, SSIWPA, which helped clarify the analysis and discussion. Their assistance is gratefully acknowledged.

6.0 REFERENCES

Hodgins, D.O., 2015a. Drought analysis and implications for Salt Spring Island, British Columbia. Technical Report.

Hodgins, D.O., 2015b. Preliminary Estimates for Storm Water Phosphorus Loads to St. Mary Lake, British columbia. submitted to the Technical Advisory Committee to the Salt Spring Island Watersheds Protection Authority, November 2015.

Moser, B.K. and G.R. Stevens, 1992. Homogeneity of variance in the two sample means test. Am Stat, **46**:19–21.

Nordin, R.N., C.J.P. McKean and J.H. Wiens, 1983. St. Mary Lake Water Quality: 1979-1981. Working Report File No. 64.080302, BC Ministry of Environment.

Ruxton, G.D., 2006. The unequal variance t-test is an underused alternative to Student’s t-test and the Mann–Whitney U test. *Behavioral Ecology*, doi:10.1093/beheco/ark016, http://beheco.oxfordjournals.org.

APPENDIX A – MOE ALGAL DATA

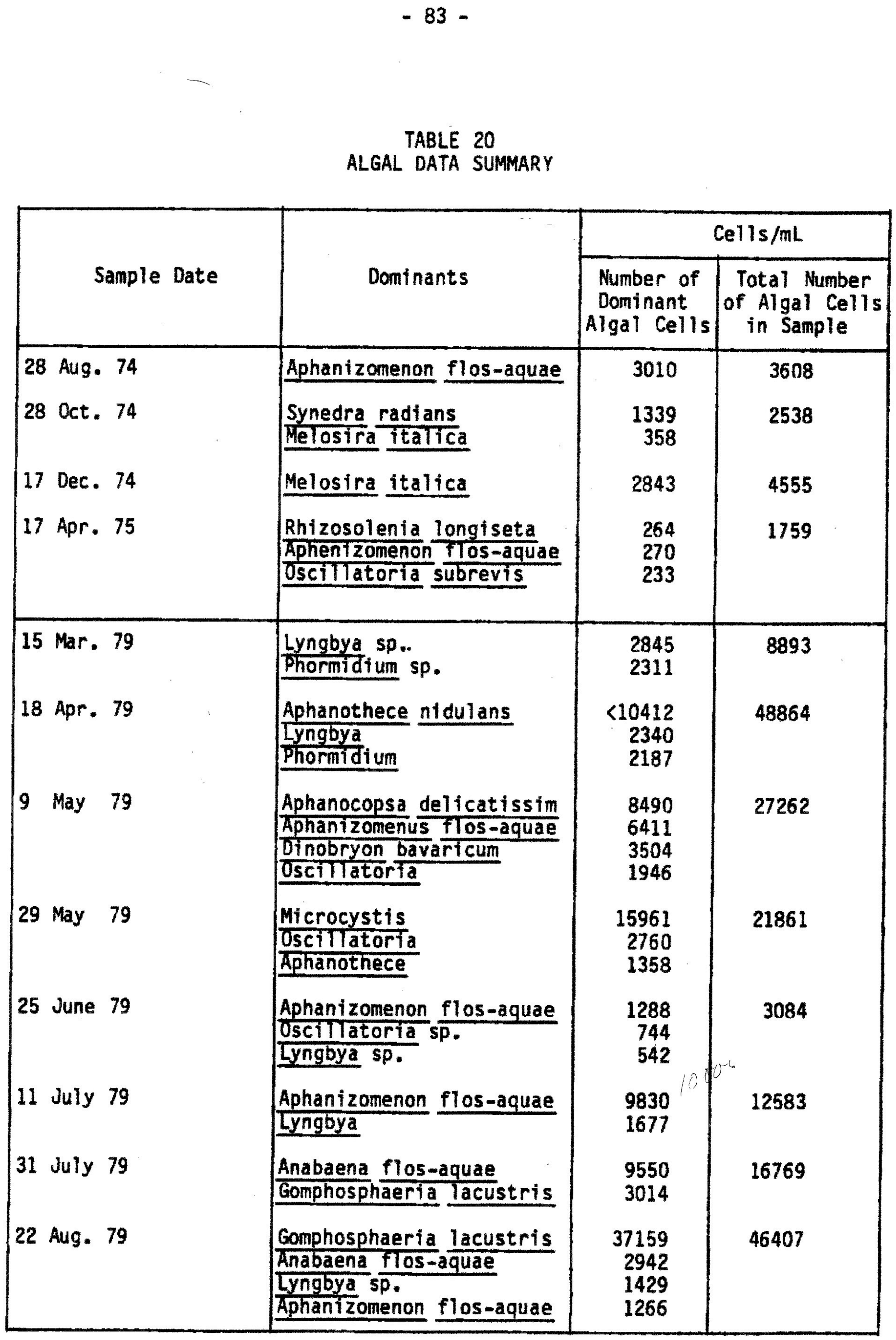


TABLE 20
ALGAL DATA SUMMARY

Sample Date	Dominants	Cells/mL	
		Number of Dominant Algal Cells	Total Number of Algal Cells in Sample
28 Aug. 74	*Aphanizomenon flos-aquae*	3010	3608
28 Oct. 74	*Synedra radians* *Melosira italica*	1339 358	2538
17 Dec. 74	*Melosira italica*	2843	4555
17 Apr. 75	*Rhizosolenia longiseta* *Aphenizomenon flos-aquae* *Oscillatoria subrevis*	264 270 233	1759
15 Mar. 79	*Lyngbya* sp.. *Phormidium* sp.	2845 2311	8893
18 Apr. 79	*Aphanothece nidulans* *Lyngbya* *Phormidium*	<10412 2340 2187	48864
9 May 79	*Aphanocopsa delicatissim* *Aphanizomenus flos-aquae* *Dinobryon bavaricum* *Oscillatoria*	8490 6411 3504 1946	27262
29 May 79	*Microcystis* *Oscillatoria* *Aphanothece*	15961 2760 1358	21861
25 June 79	*Aphanizomenon flos-aquae* *Oscillatoria* sp. *Lyngbya* sp.	1288 744 542	3084
11 July 79	*Aphanizomenon flos-aquae* *Lyngbya*	9830 1000's 1677	12583
31 July 79	*Anabaena flos-aquae* *Gomphosphaeria lacustris*	9550 3014	16769
22 Aug. 79	*Gomphosphaeria lacustris* *Anabaena flos-aquae* *Lyngbya* sp. *Aphanizomenon flos-aquae*	37159 2942 1429 1266	46407

TABLE 20. ALGAL DATA SUMMARY (Cont'd)

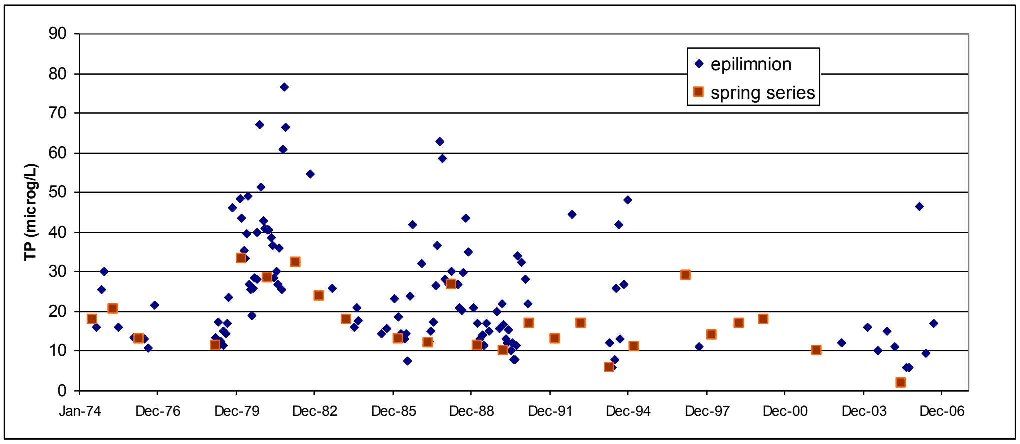
Sample Date	Dominants	Cells/mL	
		Number of Dominant Algal Cells	Total Number of Algal Cells in Sample
10 Sept. 79	*Oscillatoria* sp. *Lyngbya* sp.	27906 3759	48070
30 Oct. 79	*Oscillatoria* sp.	166000	166500
20 Feb. 80	*Oscillatoria* sp.	68825	68872
20 Mar. 80	*Oscillatoria* sp.	65792	65800
17 Apr. 80	*Oscillatoria* sp.	67204	67294
7 May 80	*Oscillatoria* sp.	37550	37830
28 May 80	*Oscillatoria* sp.	111000	114830
17 June 80	*Oscillatoria* sp.	33213	33216
8 July 80 (2 samples)	*Oscillatoria* sp.	142000/15892	151531/21515
31 July 80	*Anabaena flos-aquae* *Aphenizomenon flos-aquae* *Oscillatoria* sp.	8470 8384 5149	22521
21 Aug. 80	*Anabaena affinis*	23671	27001
17 Sept. 80	*Anabaena affinis*	5823	8342
8 Oct. 80	*Anabaena affinis* *Oscillatoria*	7260 4948	13304
22 Oct. 80	*Oscillatoria*	4900	6086
12 Nov. 80	*Chroomonas* sp. *Cyclotella* sp.	47 34	289
3 Dec. 80	*Oscillatoria* sp.	3950	4272
17 Dec. 80	*Oscillatoria* sp.	12060	12643
14 Jan. 81	*Oscillatoria* sp.	14730	14955
4 Feb. 81	*Oscillatoria* sp.	52340	52580
4 Mar. 81	*Oscillatoria* sp.	22060	22636

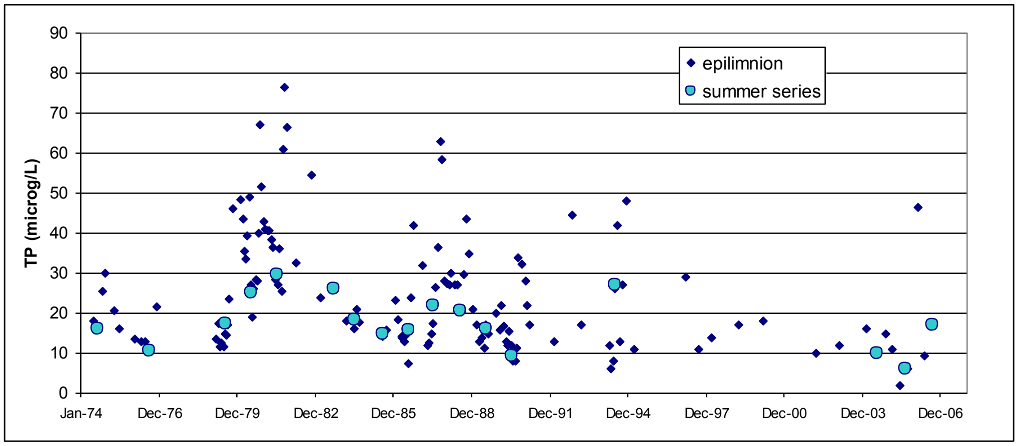
TABLE 20. ALGAL DATA SUMMARY (Cont'd)

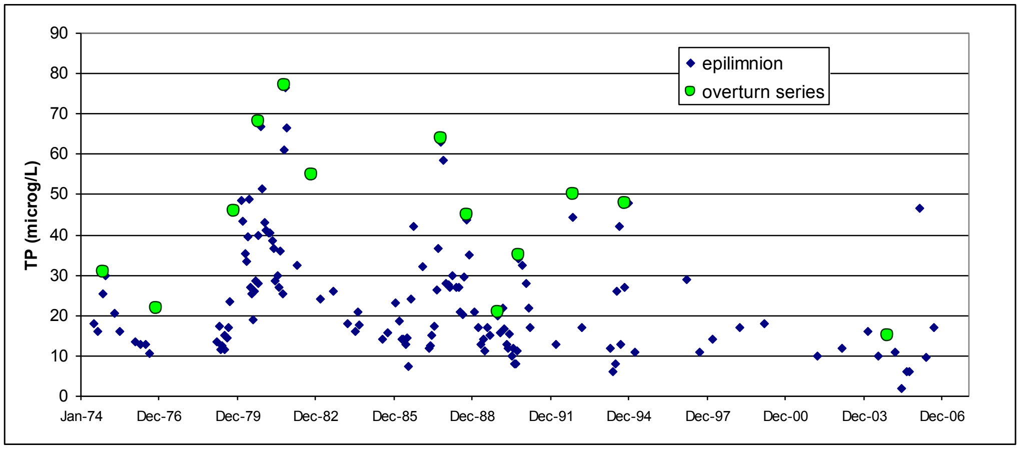
Sample Date	Dominants	Cells/mL	
		Number of Dominant Algal Cells	Total Number of Algal Cells in Sample
25 Mar. 81	*Oscillatoria*	93900	94030
21 May 81	*Oscillatoria*	132000	132122
8 July 81	*Oscillatoria*	155000	150587
28 July 81	*Oscillatoria* *Aphanizomenon*	76342 16096	95950
18 Aug. 81	*Anabaena planktonica* *Anabaena* sp.	21316 11884	33646
17 Sept. 81	*Microcystis inserta* *Anabaena levanderi*	4950 3160	8402

APPENDIX B – SAMPLE SERIES PLOTS

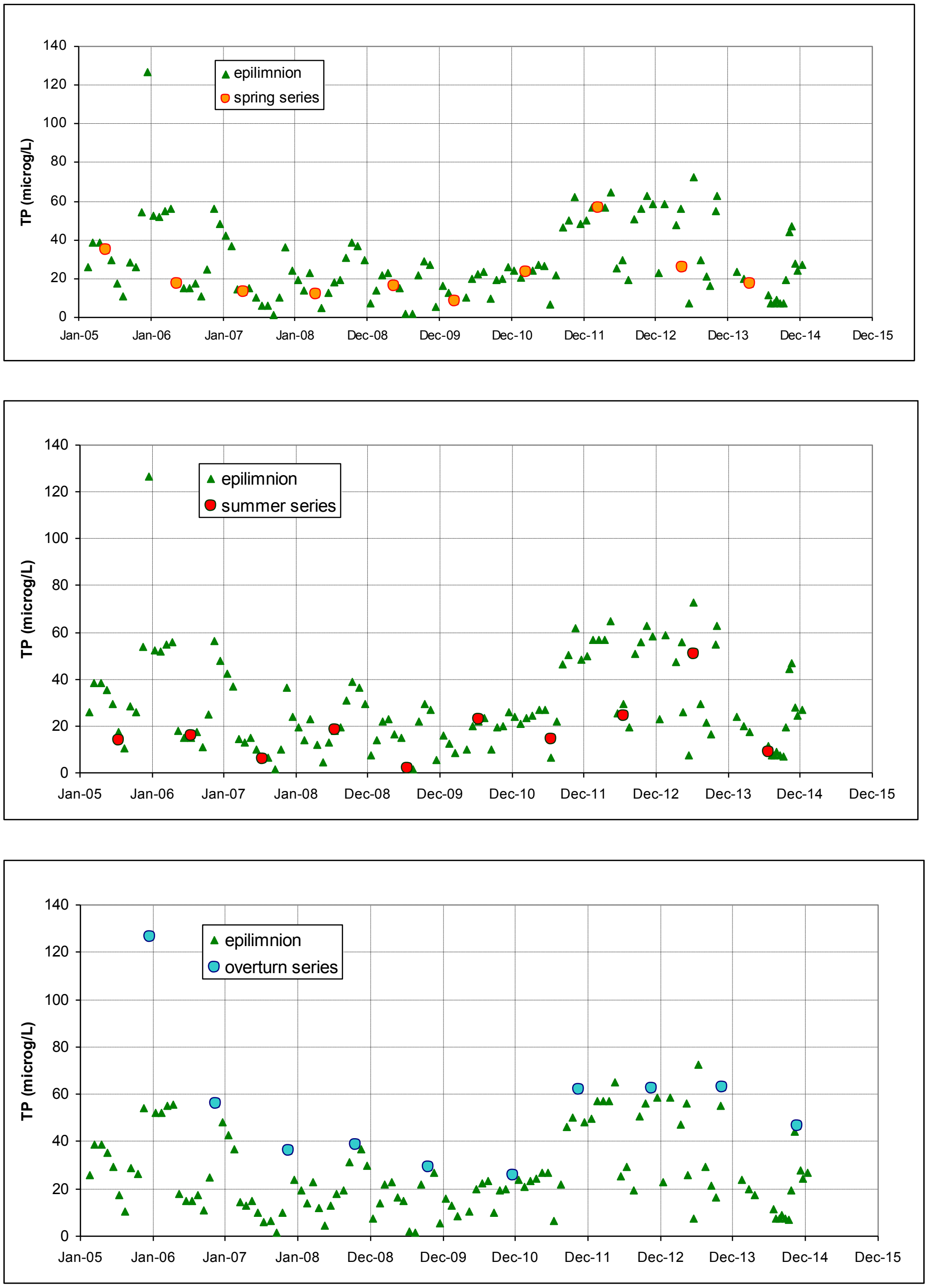
The following graphs illustrate the derived sample points extracted from each TP dataset in relation to the total time-series.







The MOE dataset.



The NSSWD dataset.