Development of Predictive Equations for Chlorophyll Concentration and Secchi Depth for Nova Scotia Lakes

Prepared for

Nova Scotia Department of Environment and Labour

By

M. Brylinsky
Acadia Centre for Estuarine Research
Acadia University
Wolfville, Nova Scotia

October 2006

Publication No. 85 of the Acadia Centre for Estuarine Research

SUMMARY

In an attempt to improve the usefulness of a recently developed model to predict the phosphorus concentration in Nova Scotia lakes based on lake morphometric and drainage basin characteristics, existing data on Nova Scotia lakes was used to develop predictive regression equations for chlorophyll concentration and Secchi depth. The regressions developed appear to be significantly different when compared to other published regressions developed for lakes in other regions of the world, and suggest that Nova Scotia lakes produce less chlorophyll per unit of total phosphorus. In addition, regressions for both chlorophyll and Secchi depth explained less variability than most published regressions. This may be due, in part, to the limited range in chlorophyll values within the Nova Scotia lake database, which in most cases is limited to two orders of magnitude in contrast to the three orders of magnitude typically available for similar studies in other regions of the world.

Development of a predictive regression equation for Secchi depth indicated that, based on the Nova Scotia lake database, Secchi depth is more strongly influenced by water color than by chlorophyll concentration. This makes Secchi depth unlikely to be a useful indicator of a lake's trophic state for Nova Scotia lakes.

Table of Contents

List of Tables

List of Figures

Page

Development of Predictive Equations for Chlorophyll Concentration and Secchi Depth for Nova Scotia Lakes

1. Introduction

The Nova Scotia Department of Environment and Labour (NSDEL) recently developed a model to predict the concentration of total phosphorus in Nova Scotia lakes based on the land use characteristics within a lake's drainage basin (Brylinsky 2004a) using an approach initially described by Dillon and Rigler (1975). As part of that project, additional study was recommended in specific areas that would either result in enhancing the accuracy of the model, or increasing its applicability to the specific types of lakes found within Nova Scotia (Brylinsky 2004b). Two priority areas identified in the initial work to improve decision making were: (1) prediction of lake trophic status based on total phosphorus concentration, chlorophyll concentration and water clarity and; (2) development of appropriate water quality objectives (WQOs) for Nova Scotia lakes.

Although a number of empirical relationships relating total phosphorus to chlorophyll concentration and water clarity are available in the literature, in most cases they have been developed for lakes on a global or large regional scale, and may not be valid for lakes on a more local scale (Omernick et al. 1991). In addition, in most cases these relationships have been developed for lakes located in regions quite different from Nova Scotia and may not be applicable within Nova Scotia. The primary objective of this study was to evaluate existing lake phosphorus and chlorophyll-water clarity relationships to determine if they are applicable to Nova Scotia and, if not, attempt to establish these relationships based on information contained in existing databases available for Nova Scotia lakes. These equations could then be incorporated into the existing Nova Scotia phosphorus model and used to assess changes in trophic state resulting form changes in total phosphorus concentration, as well as to establish appropriate Water Quality Objectives (WQOs) for Nova Scotia lakes.

2. Approach

The basic approach was to first survey and document the existing literature on lake total phosphorus and chlorophyll-water clarity relationships developed for other regions of the world and second, to test their applicability to Nova Scotia lakes using standard statistical regression procedures. This required that all existing data on total phosphorus, chlorophyll *a* concentration and water clarity for Nova Scotia lakes be tabulated into a common database along with any additional factors that may influence the relationships between these parameters.

The resulting database was then subjected to various simple and multivariate analyses to determine if existing published predictive equations were applicable to Nova Scotia lakes and, if not, how they could be modified to better represent the types of lakes found in Nova Scotia. In most cases, regression analyses were performed using log transformed data in order to satisfy the condition of normality (Hakanson and Lindstom 1997).

3. Results

3.1 Collation of Databases

The major databases identified for Nova Scotia lakes have been developed by various federal, provincial and municipal water quality survey and monitoring programs and included those held by the NSDEL and the Nova Scotia Department of Agriculture and Fisheries (NSDAF), the Bedford Institute of Oceanography (BIO) and the Halifax Regional Municipality (HRM). An additional database on Nova Scotia lakes was also obtained from the Municipality of Kings County (MKC). These were all collated into an Access$^{©}$ database. Table 3.1 lists the number of lakes for which data was available as well as the total number of records in each of these databases.

Table 3.1 Number of lakes and number of records contained in each database.

Database	Number of Lakes	Number of Records
BIO	51	201
NSDEL/NSDAF	255	1401
HRM	91	2567
MKC	10	444

A total of 30 parameters were tabulated on the physical, morphological, chemical and biological characteristics of each lake. The final complete database contains 4613 records on 407 lakes. Appendix I contains a statistical summary of this database.

3.2 Relationship between Chlorophyll and Total Phosphorus for Nova Scotia Lakes

The initial attempt to establish a predictive relationship between chlorophyll (CHA) and total phosphorus (TP) for Nova Scotia lakes required extracting the appropriate records from the compiled database. Many of the records were based on observations made at times outside of the normal growing season (generally considered to be between April and October) and at depths below the euphotic zone. In addition, some records did not contain data on both CHL and TP. Accordingly, a subset of this database that included only those records for samples collected between April and October and at water depths ≤ 6 m was used to initially evaluate this relationship. The resulting database includes a total of 2036 records on 149 lakes. Appendix II contains a statistical summary of this database.

Fig. 3.1 is a scatterplot of the relationship between CHA and TP for both the original and log transformed data.

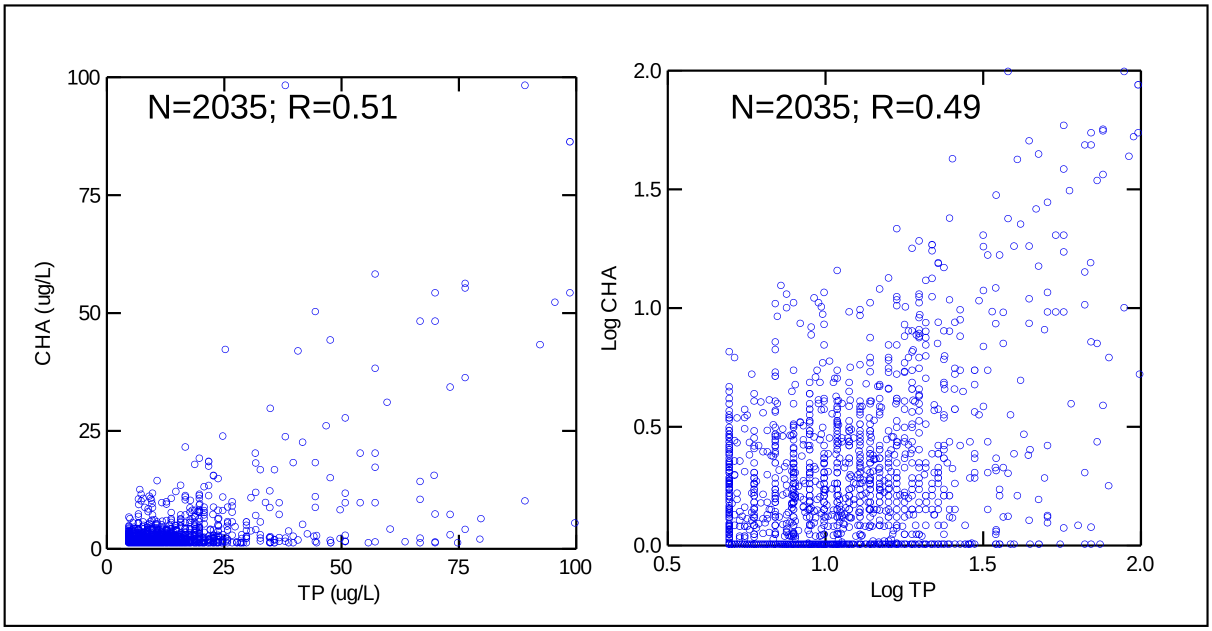

Fig. 3.1 Scatterplots of TP-CHA relationship for untransformed and log transformed data.

There is little difference in the amount of variation explained between the untransformed and transformed data. In both cases, TP explains about 25% of the variation in CHA.

A survey of the existing literature revealed that all published regressions to predict CHA from TP are based on the growing season mean values of these two parameters. Growing season means were therefore calculated for the Nova Scotia database based on those records that contained at least three measurements of TP and CHA made over the period between April and October. This resulted in a subset of the database that contained 159 records on 51 lakes.[*] A statistical summary of this database is contained in Appendix III. The resulting TP-CHA relationship (Fig. 3.2) explained about 35% of the variance.

---

[*] Because most of the data in the original databases contained only one record for each lake, this subset of the database contains considerably fewer records and lakes.

It should be noted that, based on this scatterplot, there is little evidence of a non-linear sigmoid-type relationship between CHA and TP as has been found by others (e.g., Straskraba 1980; McCaulley et al. 1989), which may be a result of the limited range of CHA and TP concentrations in the NS lake database.[**]

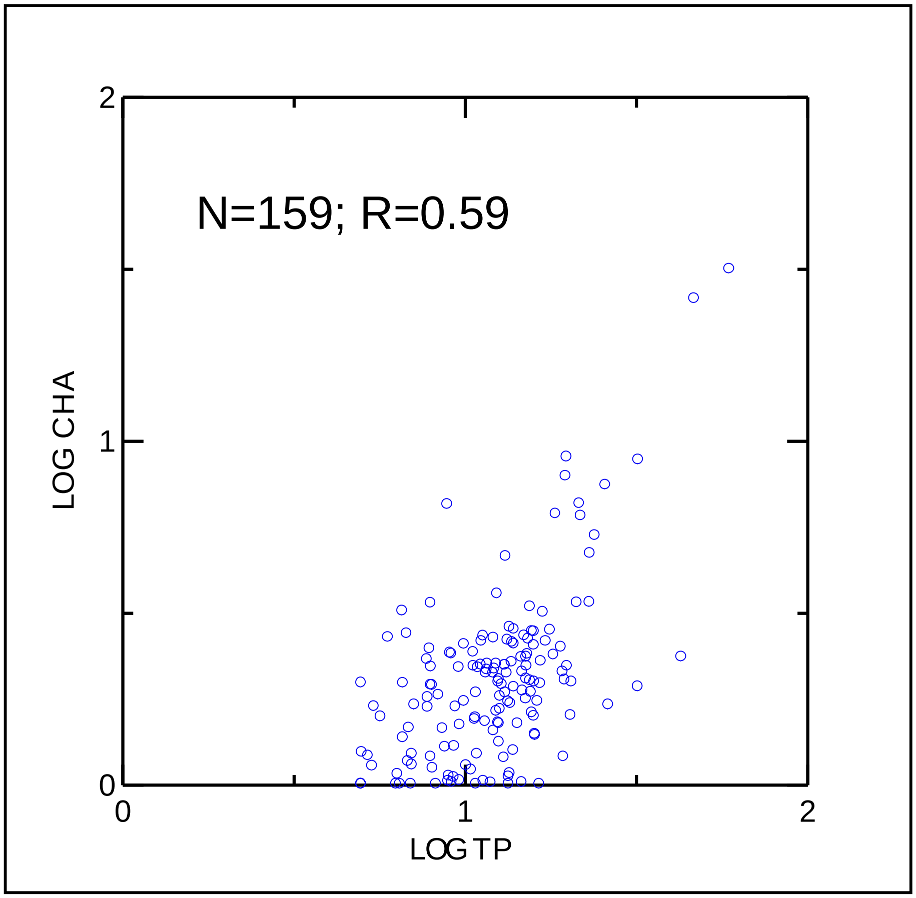

Fig. 3.2 Scatterplot of log transformed TP and CHL based on mean growing season values.

The regression equation for this relationship is as follows:

$$\mathrm{Log(CHA)} = -0.500 + 0.739\ \mathrm{Log(TP)} \quad N=159;\ R= 0.59$$

3.3 Comparison of CHL-TP Regression for Nova Scotia Lakes with other Published Regressions

Table 3.2 lists the most commonly cited regressions, based on growing season means, that have been developed for lakes in other areas of the world, and Fig. 3.3 compares the regression lines with that developed above for Nova Scotia lakes.

[**] Most studies that have developed predictive relationships between CHA and TP have utilized databases in which the values of these two parameters range over three orders of magnitude. The data for the Nova Scotia lake database spans only two orders of magnitude.

The regression equation for Nova Scotia lakes appears to differ significantly in both the slope and the amount of variance explained. The slope indicates less CHA per unit of TP and suggests that lakes within Nova Scotia lakes have a lower response to TP than lakes in other areas of the world. The amount of variance explained by the regression is also considerably less than that of regressions developed for other lake datasets.

Table 3.2. Published regression equations used to predict CHA concentration from TP concentration.

Regression Equation	Comments	Reference
Log(CHA) = -1.09 + 1.46 Log(TP) N=143; R=0.95	North American lake data set; based on mean summer (July-August) CHA	Jones and Bachmann (1976)
Log(CHA) = -0.848 + 1.213 Log(TP) N=63; R=0.88	Global lake data set	Schindler 1978
Log(CHA) = -0.150 + 0.744 Log(TP) N=165; R=0.87	Florida lakes	Canfield (1983)
Log(CHA) = -0.661 + 1.146 Log(TP) N=34; R=0.90	Alberta lakes off the Precambrian Shield	Prepas and Trew (1983)
Log(CHA) =-0.660 + 1.150 Log(TP) N=82 R=0.84	US Midwestern reservoirs	Hoyer and Jones (1983)
Log(CHA) = -0.390 + 0.874 Log(TP) N=133; R=0.83	Global lake data set	Prarie et al. (1989)
Log(CHA) = -0.369 + 1.053 Log(TP) N=533; R=0.87	Global data set using data from lakes in Europe, Japan and the US having TP <100ug/L	Brown et al. (2000)
LOG(CHA) = -0.500 + 0.739 Log(TP) N= 159; R=0.59	Nova Scotia lakes	This study

3.4 CHL-TP Regression Based on Spring TP Concentrations for Nova Scotia Lakes and Comparison with other Published Regressions

Dillon and Rigler (1974) have suggested that spring, as opposed to mean growing season, TP concentration may be a better predictor of mean growing season CHA. Although only 14 records in the Nova Scotia lakes database contained values for both spring (March) TP and mean summer CHA values, this seems to also be true for Nova Scotia lakes. Figure 3.4 is a scatterplot of the data available for Nova Scotia lakes. About 60% of the variability is explained. Table 3.3 lists a number of published regressions based on spring TP concentration and Figure 3.5 compares the regression lines with the one for Nova Scotia lakes. In this case, there is much less difference in the slope of the regression line for Nova Scotia lakes compared to that obtained for other lake datasets.

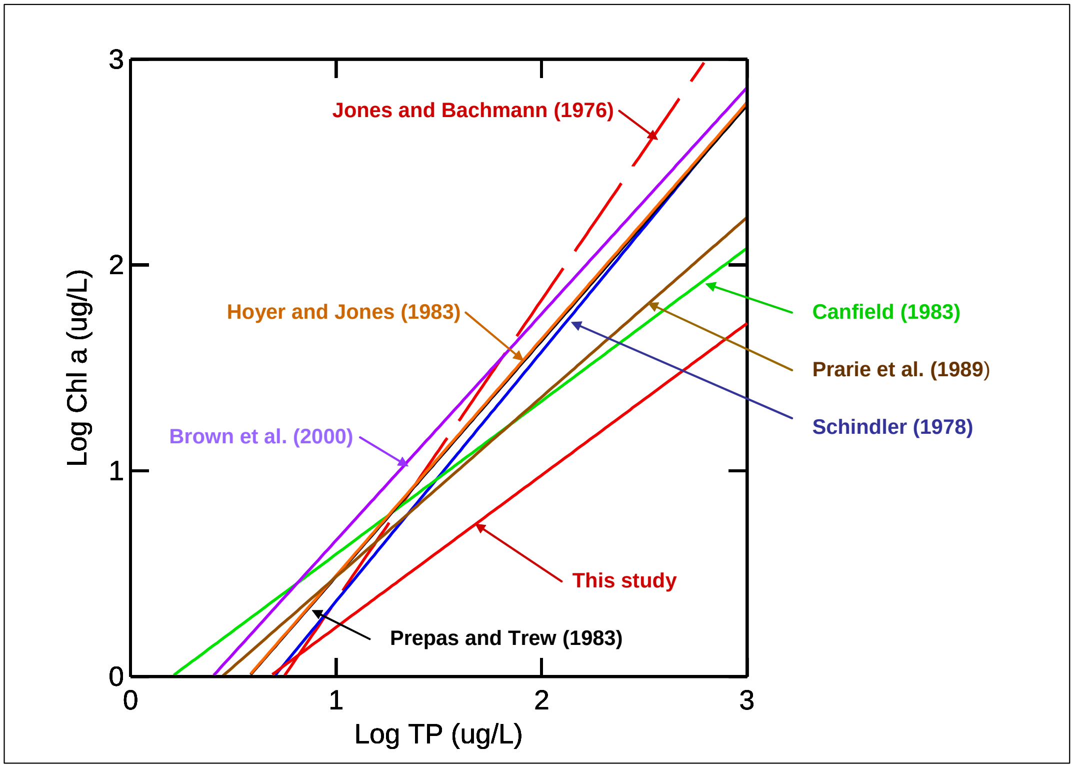

Fig. 3.3. Comparison of regression line for predicting CHA from TP for Nova Scotia lakes with published regression lines for lakes in other areas of the world.

Table 3.3. Published regression equations used to predict CHA concentration from spring TP concentration.

Regression Equation	Comments	Reference
Log(CHA) = -1.134 + 1.583 Log(TPsp) N=R=0.98	As calculated by Dillon and Rigler (1974).	Sacamoto (1966)
Log(CHA) = -1.136 + 1.449 Log(TPsp) N=46; R=0.93	Restricted to lakes having TN/TP > 12.	Dillon and Rigler (1974)
Log(CHA) = -0.676 + 1.119 Log(TPsp) N=29 R=0.82	Alberta lakes off the Precambrian Shield.	Prepas and Trew (1983)
Log CHA = -0.662 + 1.126 Log(TPsp) N=14; R=0.78	Nova Scotia lakes	This study.

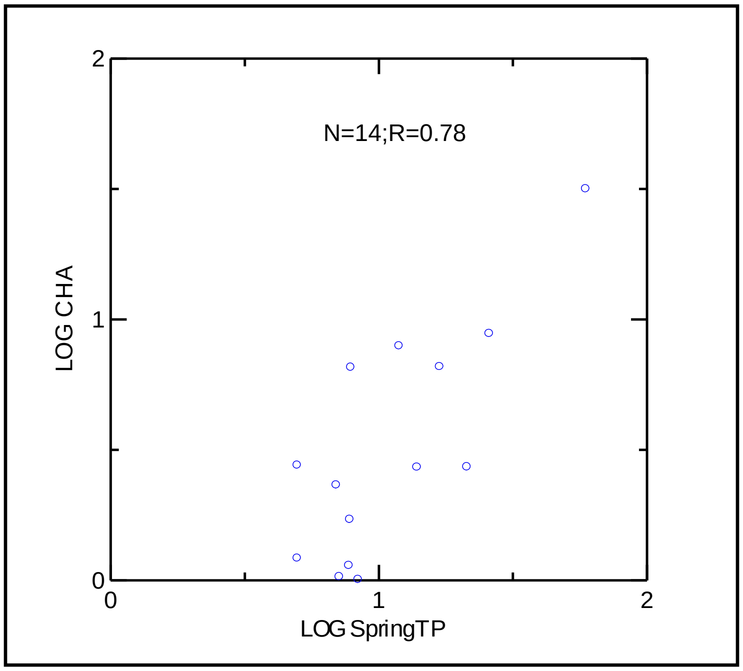

Fig. 3.4 Scatterplot of log transformed spring TP and CHL based on mean growing season CHL values.

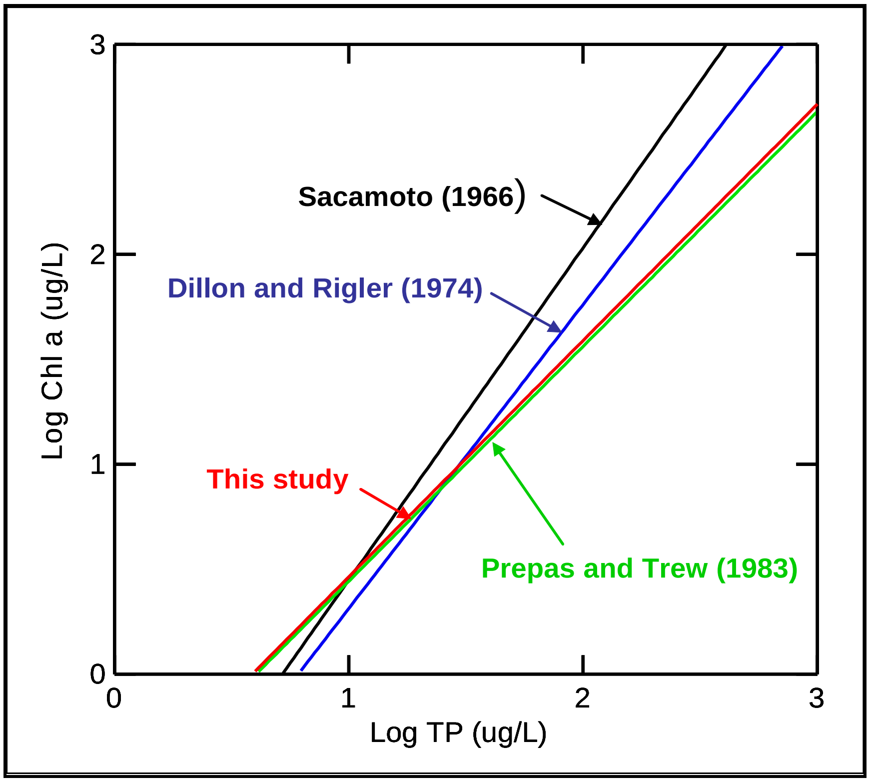

Fig 3.5 Comparison of regression line for predicting CHA from spring TP concentration for Nova Scotia lakes with published regressions lines for lakes in other areas of the world.

3.5 Additional Factors to Explain the Variability in CHA Concentration

In all studies that have developed regression equations to predict CHA concentration from TP concentration, the amount of residual variance that remains unexplained is considerable and there have been many attempts to develop multiple regression equations that would account for the unexplained variance. The parameters most often considered are other nutrients, especially Total Nitrogen (TN), water clarity, which can influence the amount of light available for photosynthesis, lake morphology and related parameters, mixing type, and zooplankton grazing. The following section considers some of these parameters in an attempt to increase the predictive capacity for CHA for Nova Scotia lakes.

3.5.1 Total Nitrogen

A number of studies have evaluated the potential importance of TN concentration as an additional limiting nutrient in lakes (Smith 1982; Canfield 1983; Dodds et al. 1989; Prarie et al. 1989). Most of these studies have shown that TN becomes important when TP concentrations are high and not limiting, and have produced multiple regression equations to predict CHA concentration from both TP and TN concentration in which TN accounts for a significant amount of the variability. These are listed in Table 3.4 along with one developed for Nova Scotia lakes.

For Nova Scotia lakes, the amount of variance explained by adding TN concentration to the regression equation is insignificant when compared to the amount of variance explained by TP concentration alone. This is not surprising since most studies that have demonstrated TN concentration to be important are for situations where TP concentrations are high, i.e., N:P ratios are <10 by weight... Based on the average growing season means of TP and TN, the Nova Scotia lake dataset contains only 12 of 137 cases in which the N:P ratio is <10.

Table 3.4. Published regression equations used to predict CHA concentration from TP and TN concentration.

Regression Equation	Comments	Reference
Log(CHA)= -1.51 + 0.653 Log(TP) + 0.548 Log(TN) N=127 R=0.98	North latitude lakes	Smith (1982)
Log(CHA) = -2.213 + 0.517 Log(TP) + 0.838 Log(TN) N= 133; R=0.90	Global lake data set.	Prarie et al. (1989)
Log(CHA) = -2.49 + 0.269 Log(TP) + 1.06 Log(TN) N=165; R=0.90	Florida lakes	Canfield (1983)
Log(CHA) = -0.894 + 0.543 Log(TP) + 0.267 Log(TN) N=137; R=0.53	Nova Scotia lakes.	This study.

3.5.2 Lake Morphology

The potential importance of lake morphology in influencing the CHA-TP relationship lies partly in lake volume relative to the size of the lake's drainage basin and partly in the depth of the lake.

The ratio of a lake's volume to drainage area, together with the amount of precipitation falling on the drainage basin, determines the lake's flushing rate. Lakes having high flushing rates would be expected to have lower CHA per unit of TP since much of the chlorophyll produced would be washed out of the lake before the level reached would grow to what would be expected based on the TP concentration (Soballe and Threlkeld 1982). The range , median and mean value of flushing rate for the mean growing season in the Nova Scotia lakes database are 0.7 - 89.6, 2.5 and 5.2 times year^{-1}, respectively. Addition of flushing rate to the CHA-TP regression did not explain a significant amount of the residual variance over that of TP alone. This is consistent with the findings of other studies. Although some studies have shown the importance of flushing rate in predicting lake TP concentration from TP loading rate (Dillon and Rigler 1975), attempts to improve the prediction of CHA from TP by considering flushing rate have not meet with much success (Hoyer and Jones 1983).

Lake depth has long been known to influence the productivity of lakes (Rawson 1955; Sakamoto 1966). Pridmore et al. (1985), in a study of 21 New Zealand lakes, was able to explain an additional 18% of the variance in CHA by considering mean depth in addition to TP. Relatively few other studies, however, have attempted to evaluate the influence of lake depth on the CHA-TP relationship. The range , median and mean value of lake mean depth for the mean growing season Nova Scotia lakes database are 1.9 - 21.8, 3.9 and 4.6 metres, respectively. A multiple regression of Log(CHA) on both Log(TP) and Log(Mean Depth) for the Nova Scotia database, however, only explained an additional 1% of the variance over Log(TP) alone.

The mixing type and degree of stratification are also largely functions of a lake's morphological characteristics. Mazumder (1994) concluded that a significant amount of the variation in the CHA-TP relationship could be accounted for if mixed and stratified lakes were considered separately. Mixed lakes had lower CHA per unit of TP than did stratified lakes. This could be due to phytoplankton being mixed to depths below the euphotic zone in mixed lakes. Havens and Nurnberg (2004), however, were unable to demonstrate a similar influence of mixing type in an analysis of a large global lake dataset.

In an effort to evaluate the influence of mixing type on the CHA-TP relationship, a simple index of mixing was calculated based on the difference between surface and bottom water temperature during late summer (July and August). The necessary temperature data was available for 100 of the 157 cases contained in the mean growing season database. This index had a range, median and mean of 0-15.0, 6.6 and 5.5 °C, respectively. When included along with Log(TP) in a multiple regression, neither the untransformed or log transformed index explained a significant amount of the unexplained variance. However, when the cases were divided into two groups based on <4°C difference and ≥4°C and the regression between Log(CHA) and Log(TP) evaluated, each of these explained more of the variance in CHA and TP than when the data was not separated into the two groups (Fig. 3.6). However a statistical test of the difference between the slopes of these regressions and that which included all of the cases indicted that there was no significant difference at the p=0.05 level.

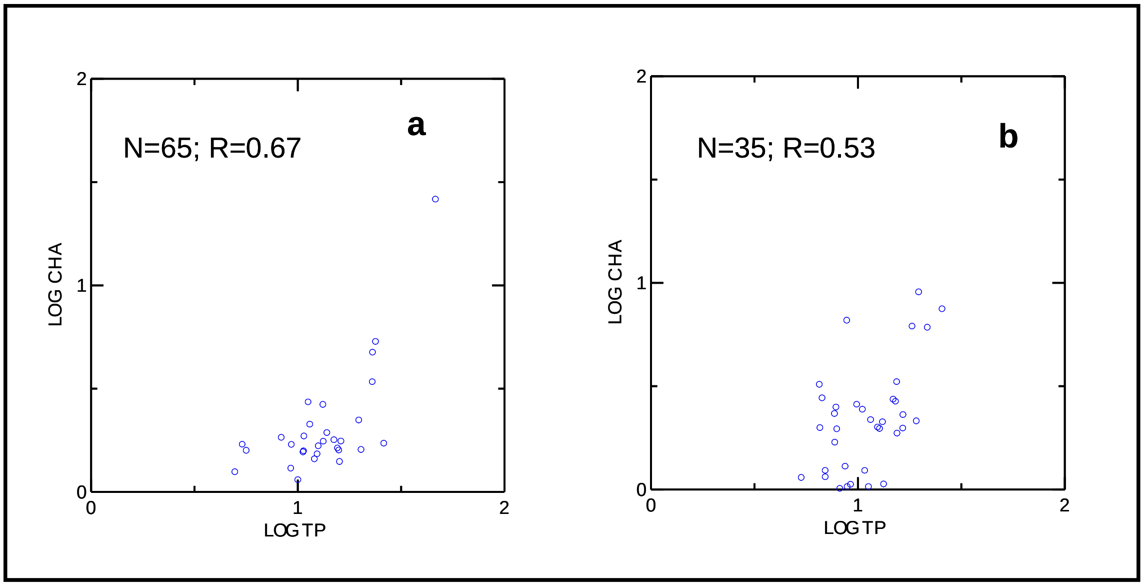

Fig 3.6 Scatterplots of Log(CHA) and Log(TP) for unstratified (a) and stratified (b) lakes.

3.5.3 Water Transparency

Water transparency is influenced by water color imparted by dissolved organic compounds (true color), especially humic and tannic acids, and by turbidity (apparent color) due to suspended particles. Under extreme conditions, high color and/or turbidity can cause light limitation to be more important than nutrient limitation. Edmundson and Carlson (1998) found that in deep, subartic Alaskan lakes, the CHA-TP relationship had a lower slope in humic lakes than in clear water lakes. Havens (2004) also found that water color was associated with a lower yield of CHA per unit of TP. Havens and Nurnberg (2004) were unable to find a similar influence of water color.

The Nova Scotia lake database contains a good deal of information on color, dissolved organic carbon (DOC), and turbidity (Table 3.5). Color and DOC are highly correlated with each other (Fig. 3.7), but turbidity does not correlate well with either of these variables.

Table 3.5 Statistical summary of parameters related to water transparency.

Parameter	N	Range	Median	Mean
DOC (mg/L)	140	0.3 – 15.2	5.2	5.4
COLOR (TCUs)	86	4.5 – 72.7	35.5	33.8
TURBIDITY (JTUs)	149	0.0 – 5.7	1.0	0.9

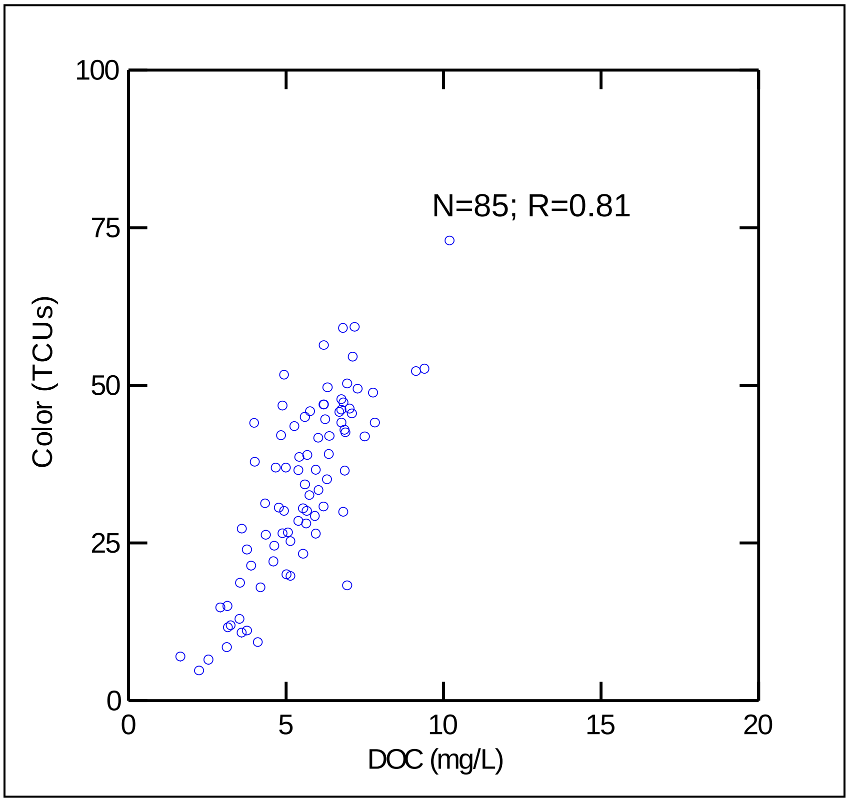

Fig 3.7 Scatterplot of DOC and color.

Separate multiple regressions of Log(CHA) with Log(TP) and Log(Color) and Log(DOC) were computed to determine if any of these variables could account for the unexplained variance based on Log(TP) alone. The addition of Log(DOC) explains an additional 10% of the variability in Log(CHA) over that of Log(TP) alone. Log(COLOR) and Log(TURBIDITY) were statistically insignificant ($p>0.05$) and did not explain any of the residual variability above that of Log(TP) alone. The results for Log(DOC) are as follows:

$$\mathrm{Log(CHA)} = -0.424 + 0.867\ \mathrm{Log(TP)} - 0.325\ \mathrm{Log(DOC)} \qquad N=140;\ R=0.68$$

3.5.4 Other Factors

In an exploratory exercise to determine if other variables contained within the database may be able to account for a significant amount of the unexplained variance in the Log(CHA)-Log(TP) relationship, the residuals of the regression were plotted against each variable. The only factors that seemed to account for a significant proportion of the residual variance were conductivity, alkalinity and pH, all of which are highly correlated with each other. Summary statistics for each of these variables is contained in table 3.6.

Table 3.6 Summary statistics for conductivity and related parameters.

Parameter	N	Range	Median	Mean
Conductivity (µSi cm^{-1})	150	48.5 - 91.6	48.5	91.6
Alkalinity (mg/L)	153	0.3 - 56.0	2.3	5.3
pH	148	3.8 - 7.8	6.3	6.3

When included along with Log(TP) in a multiple regression, each of these explained an additional 6-7% of the unexplained variance. The regression equations for each are as follows:

$$Log(CHA) = -0.795 + 0.710\ Log(TP) + 0.185\ Log(COND) \quad N=150; R=0.65$$

$$Log(CHA) = -0.795 + 0.710\ Log(TP) + 0.185\ Log(ALK) \quad N=146; R=0.64$$

$$Log(CHA) = -0.795 + 0.710\ Log(TP) + 0.185\ pH \quad N=153; R=0.60$$

3.6 .5 Combining All Factors

Based on the above results, a final multiple regression equation for predicting Log(CHA) was calculated using Log(TP), Log(DOC): and Log(COND):

$$Log(CHA) = - 0.617 + 0.820\ Log(TP) - 0.256\ Log(DOC) + 0.115\ Log(COND)$$
$$N = 137; R=0.70$$

All of the included independent variables are significant ($p \leq 0.05$). The total amount of variance explained is 48.9% and the amount of variance explained by each variable is: Log(TP)-35.8%; Log(DOC)-10.6%; and Log(COND)-2.5%.

Fig 3.8 illustrates the relationship between observed and predicted Log(CHA) concentration based on this regression equation.

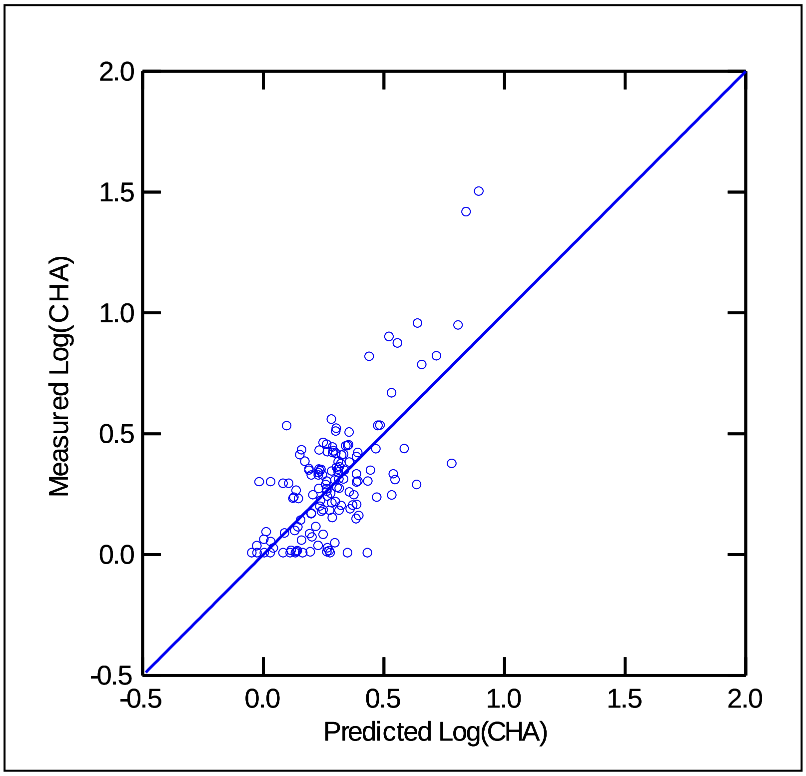

Fig 3.8 Relationship between predicted and measured mean growing season Log(CHA) concentration for the multiple regression equation based on Log(TP), Log(DOC) and Log(COND).

4. Predicting Secchi Disk Depth

Secchi depth (SD) is a crude measurement of water transparency and is often used, in combination with other parameters, to assess the trophic status of a water body (Carlson 1977). When used for this purpose, the assumption is made that Secchi Disk depth is largely a function of phytoplankton chlorophyll *a* concentration. Although numerous studies (e.g., Edmondson 1972; Jones and Bachman 1974; Carlson 1977) have shown a strong hyperbolic relationship between Secchi depth and chlorophyll *a* concentration, other factors are known to influence Secchi depth, particularly water color and non-algal turbidity (Brezonik 1978).

Table 4.1 provides summary statistics for the Nova Scotia lake database of Secchi depth and other parameters that have been demonstrated to influence Secchi depth, and Fig. 4.1 illustrates the relationships between these parameters.

Table4.1 Summary statistics for Secchi depth and related parameters.

Parameter	N	Range	Median	Mean
Secchi depth (m)	1156	0.5 - 10.0	3.6	3.9
Chlorophyll a (ug/L)	2035	1 - 98	1.3	2.8
Dissolved Organic Carbon (mg/L)	1271	0.1 - 25.0	5.1	6.3
Color (TCUs)	739	2 - 250	29	30

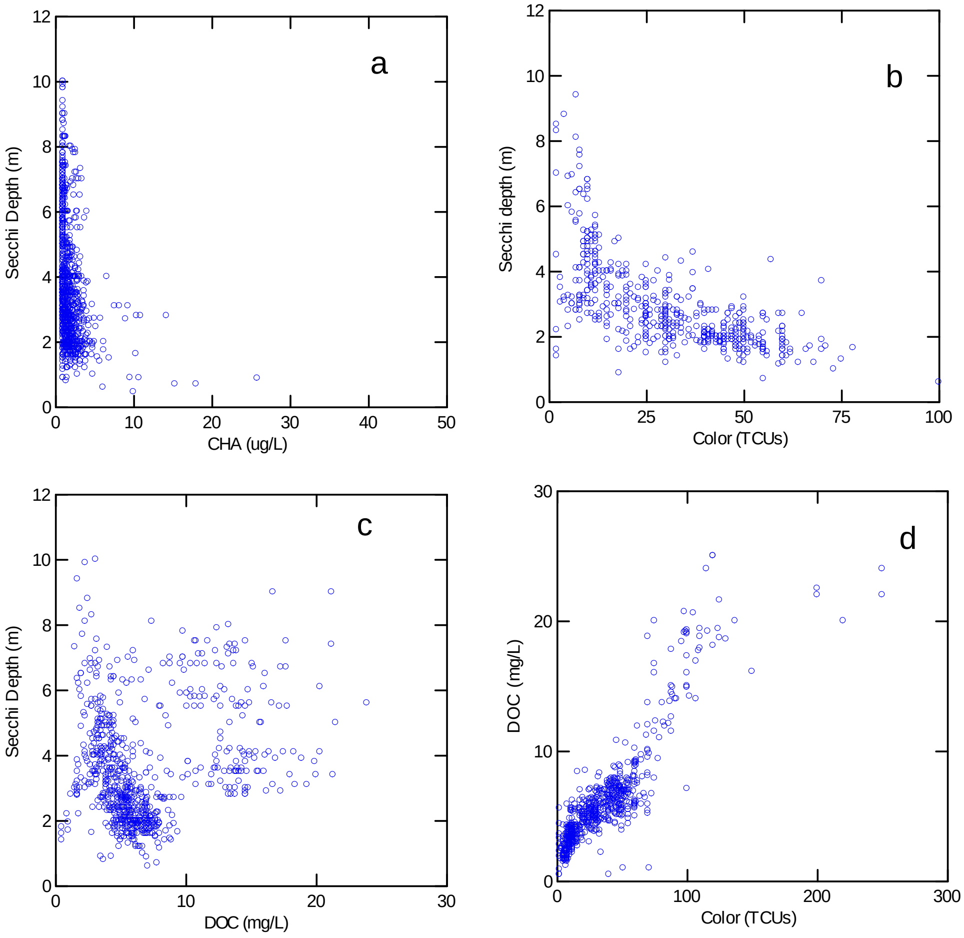

Fig 4.1. Scatterplots of Secchi depth with related parameters.

Secchi depth shows the typical hyperbolic relationship with both CHA and color, but not as clearly with DOC. Fig.4.2 is a scatterplot of Log(SD) and Log(CHA). The regression between these explained only 34.3% 0f the variability.

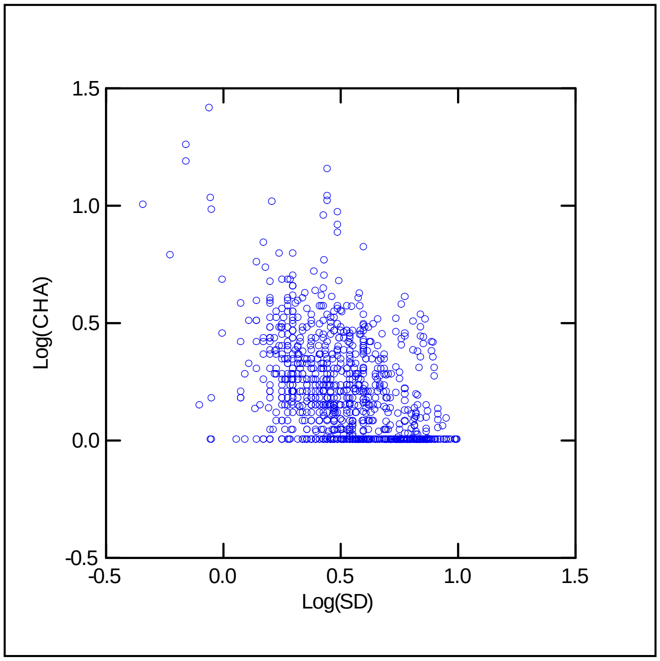

Fig. 4.2 Scatterplot of relationship between Log(SD) and Log(CHA).

A multiple regression of Log(SD) with Log(CHA) and Log(DOC) explained only 29% of the variability in Log(SD), all of which was due to CHA (Log(DOC) was statistically insignificant). This poor result for DOC is unexpected and not easily explained, but seems to be related to a large number of very odd DOC values. Inspection of Fig. 4.1c illustrates the presence of very high DOC values (>10) that are associated with relatively high Secchi depths.

A multiple regression of Log(SD) with Log(COLOR) and Log(CHA) explained about 51% of the variability in Log(SD). In this case, most (47.5%) of the variability was explained by Log(COLOR), Log(CHA) accounting for only 2.3%.

The regression equation to predict SD from Log(CHA) and Log(COLOR) is as follows:

$$\text{Log(SD)} = 0.940 - 0.175\ \text{Log(CHA)} - 0.338\ \text{Log(COLOR)} \qquad N=505;\ R=0.71$$

Table 4.2 lists published regression equations for prediction of Secchi depth. As was the case with predicting CHA from TP, the amount of variability explained by the Nova Scotia based regression is considerably less than that explained in other studies. This is likely partially due to the limited range of chlorophyll values in the Nova Scotia dataset and the strong influence of color on Secchi depth.

Table 4.2. Published regression equations used to predict Secchi depth.

Regression Equation	Comments	Reference
Ln(SD) = 2.04 – 0.68 Ln(CHA) N=147; R=0.93	Observations from 78 North American lakes	Carlson (1977)
Log(SD) = -0.63 - 0.55 Log(CHA) N=55; R=0.87	55 Florida lakes	Brezonik (1978)
Log(SD) = 0.807 – 0.549 Log(CHA + 0.03) N=143; R=0.82	North American lake data set; based on mean summer (July-August) CHA	Jones and Bachmann (1978)
Log(SD) = -0.63 - 0.55 Log(COLOR) N=55; R=0.74	55 Florida lakes	Smith (1982)
Ln(SD) = 1.25 - 0.489 Ln(CHA) N=205; R=0.79	205 Florida lakes	Canfield and Hodgson (1983)
Ln(SD) = 2.01 - 0.370 Ln(CHA) – 0.278 Ln(COLOR) N=205; R=0.88	205 Florida lakes	Canfield and Hodgson (1983)
Log(SD) = 0.630 - 0.477 Log(CHA) N=1156; R=0.24 Log(SD) = 0.940 - 0.175 Log(CHA) - 0.338 Log(COLOR) N=505; R=0.71	Nova Scotia lakes	This study.

Fig. 4.2 illustrates the relationship between predicted and measured Secchi depth based on the regression equation developed above for Nova Scotia lakes that includes Log(CHA) and Log(COLOR).

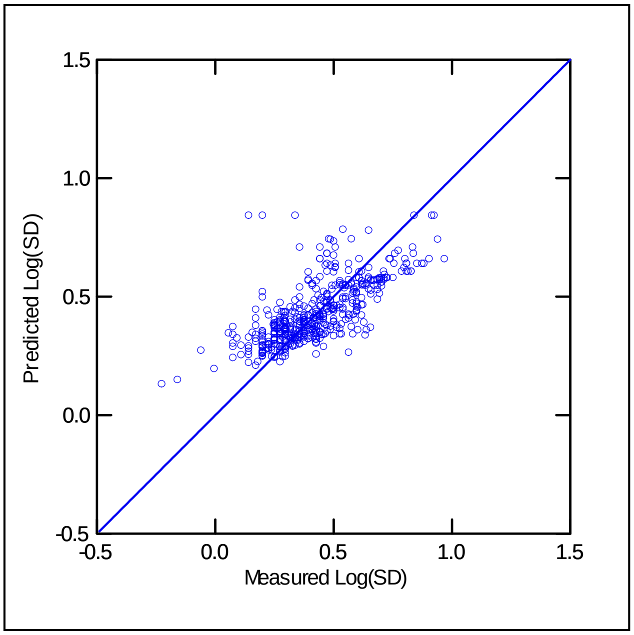

Fig. 4.3 Relationship between predicted and measured Log(SD) for the multiple regression equation based on Log(CHA) and Log (COLOR).

Using growing season mean values, slightly less variability was explained using log(SD) and Log(COLOR), but significantly more was explained using Log(DOC) and Log(CHA) In this case either regression explained about the same amount of variability. The regression equations based on mean growing season values are as follows:

Log(SD) = 0.845 - 0.182 Log(COLOR) - 0.520 Log(CHA) N=86; R=0.65

Log(SD) = 0.720 - 0.139 Log(DOC) – 0.565 Log(CHA) N=120: R=0.63

Fig. 4.4 is a scatterplot of the predicted and measured values for each of these two regressions.

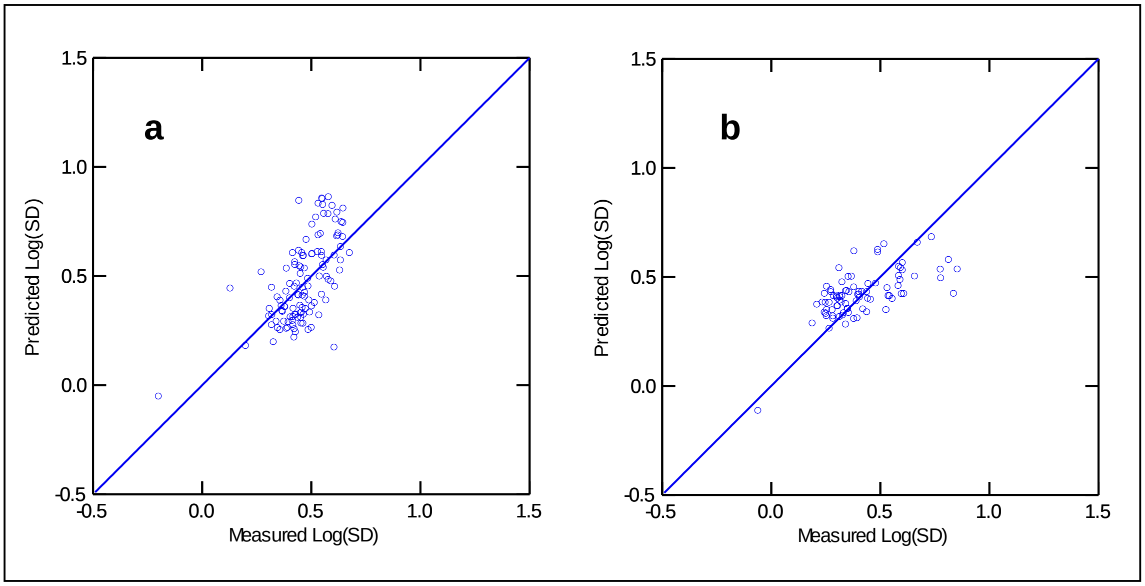

Fig. 4.4 Relationship between predicted and measured mean growing season Log(SD) for the multiple regression equation based on (a) Log(COLOR) and Log (CHA) and (b) Log(DOC) and Log(CHA).

5. Discussion

Based on this analysis it appears that previously published regression equations to predict chlorophyll concentration and Secchi depth are not applicable to Nova Scotia lakes. Although this may be partly due to the limited range of chlorophyll data for the Nova Scotia lakes compared to the databases used in other studies, the differences are great enough to suggest that they are real. Unfortunately, because the required statistical information for the other studies is not available, it was not possible to carry out tests to determine if the regression equations for Nova Scotia lakes differ significantly from those of other studies.

It is not entirely clear why the CHA-TP regression developed for Nova Scotia lakes has a slope lower that other published regressions, but it may be related to a relatively low N:P ratio for these lakes. Prarie et al (1989) looked at the variability in slopes among published CHA-TP regressions and showed that the slopes varied with TN:TP ratios, and were highest for lakes with TN:TP ratios of 23-28 by weight. The mean and median N:P ratio for the 135 cases included in the CHA-TP TN regression developed for Nova Scotia lakes (Table 3.4) were 17.2 and 16.4 respectively, and only 27 cases had an N:P ratio >23.

The large number of Nova Scotia lakes with relatively high color may also be factor (see Section 3.5.3). High color could result in light becoming a significant limiting factor for phytoplankton in instances where nutrients are present in non-limiting concentrations.

Other factors that have been shown to influence the CHA-TP relationship are suspended sediments (Hoyer and Jones 1983), macrophyte abundance (Canfield 1983; Quiros 1990) and zooplankton community structure (Pace 1984; Quiros 1990). However, none of this information is included in the Nova Scotia database and their importance could not be evaluated in this study.

Although the regressions that have been developed in this study to predict CHA leave a considerable amount of the variability in CHA unexplained, they are still useful in providing a rough guideline for establishing WQOs for TP based on a defined acceptable CHA concentration.

Because of the strong influence of color on Secchi depth, Secchi depth is unlikely to be a good indicator of trophic state for Nova Scotia lakes.

Although not discussed in this report, attempts to classify lakes into functional groups based on their chlorophyll response to total phosphorus using multivariate factor analyses and clustering procedures proved unsuccessful. This is likely a result of the great diversity of lake types present in Nova Scotia which is in turn a reflection of Nova Scotia's diverse geological, landscape and climatic characteristics.

As a final note, in compiling the various databases for this analysis it soon became obvious that some of the data contained in the original databases was incorrect. In some cases, for example, missing data had been coded as zeros, and some variables that were calculated from other variables, when recalculated, did not agree with original entries. If further analyses of the type carried in this study are planned for the future, it is important that the data contained in these databases be verified as to its accuracy. In addition, to obtain better and more confident predictive regression models, there is a real need to obtain data based on monitoring programs that capture the annual variability in the dependent and independent variables used in the equations. Chlorophyll concentrations, for example, can vary by more than two orders of magnitude within a single growing season which makes single annual measurements almost useless as an estimate of a lake's chlorophyll concentration. This has become apparent in many studies and is why all published regressions for predicting chlorophyll concentration from total phosphorus are based on annual growing season means. Progress in verifying the current Nova Scotia lake database and obtaining more data on seasonal variability would lead to more robust and reliable predictive regression equations.

6. References

Brezonik, P.L. 1978. Effect of organic color and turbidity on Secchi disk transparency. J. Fish. Res. Board Can. 35: 1410-1416.

Brylinsky, M. 2004a. User's manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making. Version 1.0. Prepared for the Nova Scotia Department of Environment and Labour. 82p.

Brylinsky, M. 2004b. User's manual for prediction of phosphorus concentration in Nova Scotia lakes: A tool for decision making. Version 1.0. Recommendations for Further Study. Prepared for the Nova Scotia Department of Environment and Labour. 13p.

Brown, C.D., M.V. Hoyer, R.W. Bachmann and D.E. Canfield. 2000. Nutrient-chlorophyll relationships: and evaluation of empirical nutrient-chlorophyll models using Florida and north-temperate lake data. Can. J. Fish. Aquat. Sci. 57:1574-1583.

Canfield, D.E. 1983. Prediction of chlorophyll *a* concentration in Florida lakes: The importance of phosphorus and nitrogen. Water Res. Bull. 19: 255-262.

Canfield, D.E. and R.W. Bachmann. 1981. Prediction of phosphorus concentrations, chlorophyll *a*, and Secchi depths in natural and artificial lakes. Can. J. Fish. Aquat. Sci. 38: 411-423.

Canfield, D.E. and L.M. Hodgson. 1983 Prediction of Secchi depths in Florida lakes: Impact of algal biomass and organic color. Hydrobiologia. 99: 51-60.

Carlson, R.E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22(2): 361-369.

Dillon, P.J. 1975. The phosphorus budget of Cameron Lake, Ontario: The importance of flushing rate to the degree of eutrophy of lakes. Limnol. Oceanogr. 20(1): 28-39.

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19(5): 767-773.

Dillon, P.J. and F.H. Rigler. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish. Res. Bd. Can. 32 (9): 1519-1531.

Dodds, W.K., K.R. Johnson and J.C. Priscu. 1989. Simultaneous nitrogen and phosphorus deficiency in natural phytoplankton assemblages: Theory, empirical evidence, and implications for lake management. Lake and Reserv. Mgmt. (5)1: 21-26.

Edmondson, W.T. 1972. Nutrients and phytoplankton in Lake Washington. Am. Soc. Limnol. Oceanogr. Spec. Symp. 1: 172-193.

Edmundson, J.A. and S.R. Carlson 1998. Lake typology influences on the phosphorus-chlorophyll relationship in subartic, Alaskan lakes. Lake and Reserv. Manage. 14: 440-450.

Hakanson, L. and M. Lindstrom, 1997. Frequency distributions and transformations of lake variables, catchment area and morphometric parameters in predictive regression models for small glacial lakes. Ecol. Modelling. 99: 171-201.

Havens, K.F. 2004. Phosphorous- algal bloom relationships in large lakes of south Florida: implications for establishing nutrient criteria. Lake and Reserv. Manage. 19: 222-228.

Havens, K.E. and G.K. Nurnberg. 2004. The phosphorus-chlorophyll relationship in lakes: Potential influences of color and mixing regime. Lake and Reserv. Manage. 20(3): 188-196.

Hoyer, M.V. and J.R. Jones. 1983. Factors affecting the relation between phosphorus and chlorophyll *a* in Midwestern reservoirs. Can. J. Fish. Aquat. Sci. 40:192-199.

Jones, J.R. and R.W. Bachmann. 1974. Limnological features of some northwestern Iowa lakes. Proc. Iowa Acad. Sci. 81: 158-163.

Jones, J.R. and R.W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. J. Water Pollut. Control Fed. 48:2176-2182.

Juday, C. and E.A. Birge. 1933. The transparency, the color, and the specific conductance of the lake waters of northeastern Wisconsin. Trans. Wis. Acad. Sci., Arts, Lett. 28: 205-259.

Mazumder, A. 1994. Phosphorus-chlorophyll relationships under contrasting herbivory and thermal stratification: predictions and patterns. Can. J. Fish. Aquat. Sci. 51: 390-400.

McCauley, E. J.A. Downing and S. Watson. 1989. Sigmoid relationships between nutrients and chlorophyll among lakes. Can. J. Fish. Aquat. Sci 46:1171-1175.

Omermick, J.M., C.M. Rohm, R.A. Lillie and N. Mesner. 1991. Usefulness of natural regions for lake management: Analysis of variation among lakes in northwestern Wisconsin, U.S.A. Environ. Manage. 15:281-293.

Pace, M.L. 1984. Zooplankton community structure, but not biomass, influences the phosphorus-chlorophyll *a* relationship. Can. J. Fish. Aquat. Sci. 41: 1089-1096.

Prarie, Y.T., M. Duarte and J. Kalff. 1989. Unifying nutrient-chlorophyll relationships in lakes. Can. J. Fish. Aquat. Sci. 46: 1176-1182.

Prepas, E.E. and D.O. Trew. 1983. Evaluation of the phosphorus-chlorophyll relationship for lakes off the Precambrian shield in Western Canada. Can. J. Fish Aquat. Sci. 40:27-35.

Quiros, R. 1990. Factors related to variance in chlorophyll-total phosphorus regressions in lakes and reservoirs of Argentina. Hydrobiologia. 200/201: 343-355.

Pridmore, R.D., W.N. Vant and J.C. Rutherford. 1985. Chlorophyll-nutrient relationships in North Island lakes (New Zealand). Hydrobiologia. 121: 181-189.

Rawson, D.S. 1955. Morphology as a dominant factor in the productivity of large lakes. Int. Ver. Theor. Angew. Limnol. Verh. 12: 164-175.

Sakamoto, M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiology. 62: 1-28.

Schindler, D.W. 1978. Factors regulating phytoplankton production and standing crop in the world's freshwaters. Limnol. Oceanogr. 23:478-486.

Smith, V.H. 1982. The nitrogen phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27(6): 1101-1112.

Soballe, D.M. and S.T. Threlkeld. 1982. Advection, phytoplankton biomass, and nutrient transformation in a rapidly flushed impoundment. Arch. Hydrobiol. 105: 187-203.

Straskraba, M. 1980. Effects of physical variables on production. *In* The functioning of freshwater ecosystems. Ed. E.D. LeCren and R.H. Lowe-McConnell. IBP 22, Cambridge University Press, Cambridge, U.K.

Appendix I Statistical Summary of Main Database

Parameter	Number of Observations	Min	Max	Median	Mean
Latitude	3572	43°50’	46°31’	44°55	-
Longitude	3572	60°11’	66°09’	63°45	-
Drainage Area (ha)	4255	11.95	63249	942	2899.4
Volume (10^6 m^3)	3962	0.022	329.50	4.56	24.42
Flushing Rate (times/yr)	4038	0.2	125.6	1.98	5.7
Maximum Depth (m)	4117	1	70	13	18
Mean Depth (m)	4105	0.1	21.8	3.9	5.8
Surface Area (ha)	4417	1.1	5735.8	98.0	297.9
Shoreline Development	3771	1.0	6.7	2.32	0.81
Surface Temperature (°C)	2498	10	27	22	21
Bottom Temperature (°C)	2315	1.3	30	13	14
Sample Date	4259	6 June 74	24 Oct 05	-	-
Sample Depth (m)	4651	0	50	0.5	4.0
TP (μg/L)	4519	5	1000	8.2	12.9
PO4-P (μg/L)	2448	0	6.8	0.10	0.06
TN (mg/L)	3510	0.002	4.2	0.20	0.22
NO_2+NO_5-N (mg/L)	2636	0	3.4	0.01	0.45
NH_3-N (mg/L)	1813	0	3	0.01	0.31
Silicate (mg/L)	1156	0	18.6	1.2	1.6
Chlorophyll *a* (μg/L)	3414	1	234	1.1	3.0
Secchi Depth (m)	1410	.4	15.0	3.5	3.9
Conductivity (μSi/cm)	4124	13	834	60	97
Hardness (mg/L)	679	0	76.8	5.5	15.4
Calcium (mg/L)	2818	0.1	57	3	4.2
pH	3835	3.3	10.1	6.1	6.0
Alkalinity (mg/L)	2774	-14.7	76	2.54	5.4
Total Dissolved Solids (mg/L)	196	1.5	165.0	10.0	18.6
Suspended Sediments (mg/L)	651	0.03	461	2.3	38.9
Dissolved/Total Organic Carbon (mg/L)	2732	0.1	29.0	4.9	6.2
Turbidity (NTU)	3769	0	71.0	1.0	1.3
Color (TCU)	1815	0	325	25	38

Appendix II Statistical Summary of Main Database Subset

Parameter	Number of Observations	Min	Max	Median	Mean
Latitude	1498	43°50	46°31	44°49	-
Longitude	1498	60°14	66°08	63°371	-
Drainage Area (ha)	1936	11.9	29769.0	927.0	3065.8
Volume (10^6 m^3)	1825	0.063	329.49	3.95	29.30
Flushing Rate (times/yr)	1853	0.2	97.8	2.0	4.8
Maximum Depth (m)	1818	2	70	14.93379	11.25623
Mean Depth (m)	1550	1.1	21.8	12	17
Surface Area (ha)	1990	1.1	5735.8	98.0	390.7
Shoreline Development	1364	1.0	4.9	2.3	0.8
Surface Temperature (°C)	952	14	27	22	21
Bottom Temperature (°C)	908	4	30	13	15
Sample Date	1696	6 June 74	24 Oct 05	-	-
Sample Depth (m)	2035	0	6	0.3	1.2
TP (μg/L)	2035	5	100	9.5	12.8
PO4-P (μg/L)	1053	0	6.8	0.02	0.09
TN (mg/L)	1541	0.003	1.70	0.19	0.21
NO_2+NO_5-N (mg/L)	944	0	0.36	0.01	0.32
NH_3-N (mg/L)	576	0	0.33	0.01	0.24
Silicate (mg/L)	647	0	9.0	1.1	1.5
Chlorophyll *a* (μg/L)	2035	1.0	98.0	1.3	2.8
Secchi Depth (m)	1156	0.5	10.0	3.6	3.9
Conductivity (μSi/cm)	1849	13	809	56	100
Hardness (mg/L)	374	0	75.4	5.3.	14.4
Calcium (mg/L)	997	0.1	26.0	3.3	4.8
pH	1778	3.3	10.1	6.2	6.2
Alkalinity (mg/L)	1559	-11.7	76.0	2.3	5.4
Total Dissolved Solids (mg/L)	120	1.5	165.0	11.8	21.9
Suspended Sediments (mg/L)	339	0.03	0	1.5	32.4
Dissolved/Total Organic Carbon (mg/L)	1271	0.1	25.0	5.1	6.3
Turbidity (NTU)	1733	0	70	1	0.8
Color (TCU)	739	2	250	29	35

Appendix III Statistical Summary of Mean Growing Season Database

Parameter	Number of Observations	Min	Max	Median	Mean
Latitude	110	44°30	46°09	44°51	44°59
Longitude	110	61°11	65°48	63°43	63°67
Drainage Area (ha)	158	20	29769	927	3014
Volume (10^6 m^3)	152	0.13	329.49	4.84	20.88
Flushing Rate (times/yr)	156	0.7	89.6	2.47	5.26
Maximum Depth (m)	140	3	52	11	14.3
Mean Depth (m)	156	2	22	4	4.6
Surface Area (ha)	159	4.3	5735.8	105.0	370.2
Surface Temperature (°C)	69	17	24	22	21.4
Bottom Temperature (°C)	66	0	15	7	5.5
Sample Date	159	17 July 74	13 Aug 02	-	-
Sample Depth (m)	159	0	4.0	0.3	0.9
TP (μg/L)	159	5.0	59.5	12.6	13.4
PO4-P (μg/L)	115	0.001	2.076	0.002	0.056
TN (mg/L)	135	0.06	0.65	0.21	0.21
NO_2+NO_5-N (mg/L)	66	0.00	0.28	0.03	0.04
NH_3-N (mg/L)	46	0.01	0.23	0.03	0.03
Silicate (mg/L)	64	0.06	7.53	0.94	1.34
Chlorophyll *a* (μg/L)	159	1.0	31.4	1.9	2.5
Secchi Depth (m)	129	0.9	7.2	2.8	3.3
Conductivity (μSi/cm)	150	20.1	650.0	48.6	91.6
Hardness (mg/L)	32	2.2	75.4	12.1	19.7
Calcium (mg/L)	75	0.4	24.2	3.5	5.7
pH	153	3.8	7.8	6.3	6.3
Alkalinity (mg/L)	148	-0.3	56.0	2.3	5.3
Total Dissolved Solids (mg/L)	12	8.2	55.0	28.5	30.2
Suspended Sediments (mg/L)	23	0.4	197.5	1.5	24.7
Dissolved/Total Organic Carbon (mg/L)	140	0.3	15.2	5.16	5.4
Turbidity (NTU)	149	0	5.7	1.0	0.9
Color (TCU)	86	5	72	36	34