Paleolimnological assessment of the eutrophication history of Tyhee Lake, British Columbia

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Background

Humans have accelerated the eutrophication process in many lake regions (Vollenweider, 1980), as the export of limiting nutrients, such as phosphorus (Prairie and Kalff, 1986) and nitrogen (Duarte and Kalff, 1989) compounds, to lakes has increased. Direct nutrient inputs include sewage, domestic detergents and industrial waste. Some inputs are more diffuse, such as from urban runoff, agricultural fertilizers, pastures, and erosion from road construction and deforestation. In British Columbia, a variety of mitigation methods have been proposed (Rysavy and Sharpe 1995) and applied (Henderson-Sellers and Markland, 1987) in efforts to recover pre-impact water quality conditions. There is concern, however, that mitigation efforts may be being applied to naturally eutrophic lakes, for which restoration is unnecessary and probably futile. Because data on pre-disturbance lake conditions are lacking, paleolimnology is the only method available to determine the natural background conditions of eutrophic lakes. Moreover, it is the only method for reconstructing the effects of past cultural disturbances, as long-term monitoring data are lacking.

Paleolimnologists have repeatedly shown that lakes and their biota are very sensitive to events occurring within their catchments (Smol, 1992). Briefly, the science deals with assessing the physical, chemical and biological characteristics of fossil remains in dated sedimentary profiles, and using the fossils to infer past environmental conditions. The study of algal remains (especially diatoms) has allowed reliable reconstructions of eutrophication in BC (Reavie et al. 1995a,b; Hall & Smol 1992). Of the many biomarkers available to paleolimnologists, diatoms are the most widely used group of indicators for eutrophication research (Dixit et al. 1992). Diatom valves are particularly useful in paleolimnological studies because their siliceous cell walls are resistant to dissolution; diatom taxonomy is well defined, in that the size, shape, and sculpturing of their valves are taxon-specific; many species have well-defined environmental optima and tolerances; they are present in almost all aquatic environments, including lakes, rivers, wetlands, oceans and soils; and fossil assemblages are often abundant and diverse (Dixit et al., 1992).

Use of diatoms in paleolimnological studies of trends in lake trophic status can provide information to policy makers on the effects of cultural activities (Smol, 1992). Quite often, human activities result in degradation of lakewater quality, and paleolimnology is the only way to determine the extent of environmental damage, as long-term monitoring data are not available. For example, Stockner and Benson (1967) used fossil diatoms to track 80 years of sewage enrichment in Lake Washington. They observed a shift from *Melosira italica* to the eutrophic *Fragilaria crotonensis* coinciding with the establishment of the city of Seattle. Suburban housing development was shown by Brugam (1978) to cause diatom communities to shift to hypereutrophic assemblages. Brugam and Vallarino (1989) evaluated trophic disturbance in short cores from four western Washington lakes, and demonstrated that prior to settlement and land perturbation, these lakes were oligotrophic. Following settlement, *Asterionella formosa*, an indicator of elevated nutrient concentrations, increased in abundance, corresponding to deforestation and land development in the lakes' watersheds. O'Sullivan (1992) documented the limnological consequences of sewage inputs, land use, fertilizer application and numbers of livestock, to infer 75 years of eutrophication trends in southwest England. The water quality in his study lake eutrophied from "permissible" to "dangerous" levels in the period from 1905-1980. Reavie et al. (1995a) used diatoms in a paleolimnological assessment of six inland BC lakes to determine that three of the lakes had become severely eutrophic due to human disturbance, whereas the other lakes were likely naturally eutrophic. These findings have important implications for lake management.

A recent environmental assessment of Tyhee Lake, BC (Rysavy and Sharpe 1995) demonstrated that water quality is in need of improvement. While several lake management policies have been considered, the natural conditions of the lake are still unknown. In this study, we document the diatom assemblages preserved in the recent sediments of a 210Pb-dated lake sediment core, and, using recently-developed diatom transfer functions (Reavie et al. 1995b, B. Cumming et al. in prep.), reconstruct past changes in lake trophic status.

Study Region

Tyhee Lake is located in inland BC at 54°45' N, 127°15' W, within the Caribou Aspen - Lodgepole Pine biogeoclimatic zone. It is a 318 hectare dimictic lake (other morphometric data are summarized in Table 1). During the most strongly stratified periods, deep waters become anoxic (Portman 1992). Total phosphorus measurements from May 1995 range from 0.025 to 0.056 mg L^{-1}, indicating that Tyhee is a mesotrophic to eutrophic system (Wetzel 1983). The littoral zone covers up to 30% of the surface area, and during the ice-free season it is densely colonized by aquatic plants (e.g. *Myriophyllum sibiricum*, *Potamogeton* spp., *Lemna* spp., *Spirodela polyrhiza*, *Wolffia columbiana* and *Ceratophyllum demersum*). Tyhee Lake's watershed includes waterfowl nesting areas, wetlands and beaches (~45% of shoreline), as well as specific anthropogenic uses such as boat launches, a provincial park, and a seaplane base. (residents)

Materials and Methods

A 51 cm sediment core was collected by Ministry personnel at the deepest part of the lake using a modified Kajak-Brinkhurst (KB) gravity corer equipped with a 6.35 cm inside diameter core tube. The core was sectioned by Ministry personnel using a close-interval extruder and 1 cm slices were stored in Whirlpak® bags prior to subsampling. At PEARL, subsamples of sediment were taken for ^{210}Pb dating and diatom preparation.

Sediment subsamples (approx. 30 g) of selected intervals were weighed, oven-dried (24 hr at 110 °C) and ground in a mortar. Samples were reweighed to determine dry weight and submitted to Mycore Ltd. for ^{210}Pb analysis. The dating models were run at PEARL. ^{210}Pb dating is calculated from determinations of ^{210}Po, a decay product of ^{210}Pb. Quantitative measurements were made using alpha spectroscopy (Cornett et al. 1984). Unsupported ^{210}Pb was calculated by subtracting supported ^{210}Pb (the baseline ^{210}Pb activity naturally present in the sediments) from total activity at each level. Dates were then determined from unsupported isotopes using the constant rate of supply (C.R.S.) model (Appleby and Oldfield 1978); a computer program designed by Binford (1990) was used to perform these calculations. ^{210}Pb dating is limited to ~150 years before present, so extrapolations beyond this period were made based on calculated sediment accumulation rates for the lowest intervals of the core.

Diatom Preparation

Seventeen sediment intervals were selected for diatom analysis. Subsamples of wet sediment (0.3 - 1.0 g) were heated for one hour in a mixture of potassium dichromate and sulphuric acid to digest organic matter. Samples were then repeatedly washed in distilled water and allowed to settle until they were clear and free of residual acid. The siliceous remains were settled onto coverslips, and the coverslips were mounted on glass slides using Naphrax®. For each slide, at least 300 diatom valves were identified and counted along transects under oil immersion at 1000X. Diatom taxonomy was based primarily on Krammer and Lange-Bertalot

(1986, 1988, 1991a, b), Camburn et al. (1984-1986), and Patrick and Reimer (1966). Chrysophyte cysts were also enumerated and expressed relative to the diatom sum (Smol 1985).

Inferring Total Lakewater Phosphorus

The diatom transfer functions we used to reconstruct lakewater total phosphorus concentration (TP) from fossil diatom assemblages were constructed by determining the relationship between water chemistry variables and diatom distributions in the surface sediments of BC lakes. Two models were used: 1) based on 64 calibration lakes, to reconstruct TP levels during the ice-free season (spring and summer) (Reavie et al. 1995b); and 2) based on 111 calibration lakes, to reconstruct late summer TP (B. Cumming et al. in prep.). Briefly, the models operate as follows: Several BC lakes (a "training" or "calibration" set) were selected. In this case, one set contained 64 lakes, which were sampled during spring and summer seasons, and the other contained 111 lakes, which were sampled during late summer. At each lake, several physical (e.g. depth, surface area, watershed area, temperature) and chemical (e.g. total phosphorus, conductivity, salinity, oxygen, nitrates, etc.) environmental variables were measured. Surface sediment, containing the most recent fossil diatom assemblages, was also obtained from each lake. Once the diatom species were identified from each sample, the relationships between environmental variables and diatom assemblages were determined statistically (see review by Charles & Smol (1994) for details). Essentially, the environmental "preferences" of the diatom taxa were determined. Variables (in this case, total phosphorus) with a strong influence on the species patterns in the diatom assemblages were deemed suitable for reconstructive applications. The transfer functions created by the merging of environmental and diatom data allows the inference of past (usually unknown) environmental conditions from fossil diatom assemblages in sediment cores.

Quantitative TP inferences were performed using the computer program WACALIB version 3.3 (Line et al. 1994). The distribution of TP measurements for both calibration sets (Reavie et al. 1995b, B. Cumming et al. in prep) was skewed toward the oligotrophic extreme of the spectrum, so calculations were performed using transformed (ln(TP + 1)) data (see Birks et al. 1990 or Birks 1995 for details). The diatom-inferred total phosphorus concentration (DI-TP) values generated by WACALIB were subsequently back-transformed.

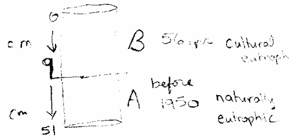
Results and Interpretations

^{210}Pb analyses

Our geochronological analyses indicated a fairly consistent sequence of sediment accumulation. An exponential increase in ^{210}Pb concentration from bottom to surface sediments was measured (Fig. 1), hence we are confident that a relatively undisturbed sedimentary profile had been obtained for Tyhee Lake. ^{210}Pb counts were converted to calendar years (Fig. 2), and it appears that the core represents ca. 300 or more years of sediment accumulation. Anthropogenic influence is assumed to be greatest in intervals from ~20-0 cm depths, because this interval represents the late 19th and the 20th century.

Qualitative Assessment of Diatoms

Sixty-four diatom taxa were identified in the Tyhee Lake core. Only four species (*Fragilaria pinnata*, *F. construens*, *F. brevistriata* and *Stephanodiscus minutulus*) occurred in relative abundances greater than 10%, so a large proportion of the taxa were quite rare. The core has been roughly divided into two zones (A and B). Zone A (51-9 cm) represents all intervals



earlier than ca. 1950, and zone B (9-0 cm) represents approximately the last ca. 56 years.

In the Tyhee Lake core (Fig. 2), *Fragilaria construens*, *F. pinnata* and *F. brevistriata* are the most common taxa in all intervals below ~1950 (Zone A). Other *Fragilaria* taxa are also present, but no obvious shifts are noted during that period. The eutrophic indicator *Stephanodiscus minutulus* first appears in significant relative numbers in the late 1700s or early 1800s, and fluctuated in relative abundance until ~1950. The relative proportions of benthic species fluctuated between 80% and 100% throughout Zone A. The assemblage of Zone A suggests that Tyhee lake is somewhat naturally eutrophic (perhaps mesotrophic), primarily due to the early presence of *Stephanodiscus*. While *Fragilaria* taxa tend to be ubiquitously distributed (Patrick and Reimer 1966), they have often been found in slightly eutrophic BC environments (e.g. Reavie et al. 1995b). For example, *Fragilaria pinnata* is difficult to classify ecologically because it occurs in both high and low nutrient environments (Christie and Smol 1993; and personal observations).

Since ~1950 (9-0 cm; Zone B), benthic taxa decreased substantially to be replaced in relative abundance by planktonic diatoms. The notable changes are a shift from an assemblage dominated by *Fragilaria* spp., to one dominated by *Stephanodiscus minutulus*. During this period, the planktonic taxa *Cyclotella bodanica* var. *lemanica* and *Fragilaria crotonensis* also increased. The latter taxon is often considered a good indicator of cultural eutrophication. Total planktonic diatoms increased from 20% to 51% of the assemblage. These changes are an indication of significant additional eutrophication within the last four decades. (40 yrs)

In summary, a qualitative assessment of diatom species changes indicates that Tyhee Lake is naturally productive (mesotrophic), but has eutrophied significantly in response to human impacts in the late 20th century

Total Phosphorus Reconstruction

Of the 64 taxa encountered in the core, 38 of those were in common with Reavie et al. (1995b)'s TP model, and 34 were in common with B. Cumming et al. (in prep.)'s model. However, because many of the taxa in the Tyhee core were rare (many were identified only once), the proportion of diatoms that also occurred in the calibration lake samples was never less than 92%. Hence we have very good core/model analogues. To reiterate, the 64-lake model (Reavie et al. 1995b) reconstructs spring/summer TP because environmental measurements from those seasons were related to diatom assemblages for the construction of the transfer function. Meanwhile, the 111-lake model (B. Cumming et al. in prep.) reconstructs late summer TP, because the lake set, and assorted limnological data, were sampled in late summer.

Diatom-inferred total phosphorus concentration (DI-TP), using the Reavie et al. (1995b) model, indicates that Tyhee was likely a naturally eutrophic lake, as spring DI-TP fluctuated between 35 and 43 μg L^{-1} during dates prior to European settlement (i.e. before 1850) (Fig. 3). DI-TP continued to fluctuate in this manner until the 1960s, when levels increased to ~46 μg L^{-1}. Levels decreased to ~43 μg L^{-1} in the 1980s, and increased again, to ~49 μg L^{-1}, in the most recent sediments. While this profile denotes erratically-shifting nutrient conditions, the general increase in DI-TP within the last 40 years is a convincing indication of eutrophication caused by nutrient loading, consistent with the qualitative assessment of the diatom species changes noted earlier. It is difficult to compare inferred results with measured TP because inferred values in this reconstruction represent an "average" of lakewater TP during the spring and summer seasons contained in each interval, whereas measured data were determined only by sporadic spot samples. However, based on TP measurements from 1985 to 1995, recent lakewater TP concentrations in the surface waters of Tyhee Lake measured as high as ~53 μg L^{-1} (BC

Environment, unpublished data), but averaged ~25 μg L^{-1}. While this average is much lower than the recent DI-TP, we must re-emphasise that spot samples are an unreliable indication of trophic conditions.

The late-summer DI-TP history of Tyhee Lake (using the B. Cumming et al. in prep., model) indicates TP concentrations fluctuated at relatively low levels (7.7 - 8.9 μg L^{-1}) until the early 1900s, after which a modest increase occurred. Above 15 cm, DI-TP fluctuated slightly, but tended to increase, peaking at 9.7 μg L^{-1} at the 0-1 cm interval. While these TP levels are not considered eutrophic by standard interpretations (Wetzel 1983), modern TP reconstructions closely resemble actual summer TP measurements. For example, a spot sample (BC Environment, unpublished data) from August 1992, measured TP levels at 8 μg L^{-1}. These apparently oligotrophic nutrient levels are not surprising during late summer, as this is the time when thermal stratification tends to be most pronounced in dimictic lakes such as Tyhee. During stratification, the biota, often blooms of blue-green algae, deplete epilimnetic waters of nutrients. Because complete mixing of the lake cannot occur at this time, resuspension of nutrients from the sediments is not possible, and the surface waters are low in TP. Nonetheless, an overall increase in late-summer TP has occurred in the last ~80 years, indicating anthropogenic impacts related to excess nutrient inputs.

Cyst/Diatom ratio

The relative numbers of chrysophyte stomatocysts to diatom valves decreased from as high as 0.25 during pre-settlement times, to trace levels (less than 0.05) during the last ~90 years (Fig. 2). Chrysophytes tend to thrive in low nutrient conditions, and tend to be uncommon in eutrophic waters (Sandgren 1988). Smol (1985) used a similar method to interpret trophic histories of Ontario lakes, and noted that a decreased relative abundance of cysts was attributed to smaller chrysophyte populations during eutrophic periods in the lake's history. The same appears to be true for Tyhee Lake; a relative decrease in chrysophyte numbers due to increased nutrient loading this century.

Summary

1) A 51-cm sediment core was obtained from Tyhee Lake, BC, and ^{210}Pb dating techniques indicate that it contains ~300 years of sediment accumulation.

2) Diatom microfossils in the sedimentary profile indicate that Tyhee Lake is probably naturally productive (mesotrophic), but after ~A.D. 1950, significant eutrophication occurred due to anthropogenic influences in the watershed.

3) Diatom-inferred total phosphorus concentrations, determined using diatom-based transfer functions for BC lakes, corroborate the eutrophication trend indicated by qualitative diatom analyses.

4) A decrease in chrysophyte stomatocysts relative to diatom remains also indicates eutrophication within this century.

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Table 1: Summary of morphometric data for Tyhee Lake, BC.

Attribute (units)	**Value**
Elevation (m)	549
Surface area (ha)	318
Volume (dam^3)	35.278
Mean depth (m)	11.1
Maximum depth (m)	22.2
Perimeter (m)	9754
Littoral area (% surface area)	20-30
Mean water retention time (years)	5
Mean flushing rate (year^{-1})	0.2

Figure captions

Figure 1. Plot of ^{210}Pb counts in the Tyhee Lake sediment core, illustrating exponential radioactive decay with depth.

Figure 2. Stratigraphies of the dominant siliceous microfossils for Tyhee Lake (relative frequencies, %). Diatom taxa were combined ecologically to generate the categories "total benthics" and "total planktonics".

Figure 3. Profiles of inferred total phosphorus concentrations for Tyhee Lake. Spring/summer reconstructions were generated using Reavie et al. (1995b)'s model, and late summer reconstructions were generated using B. Cumming et al. (in prep.)'s model.

Fig 2

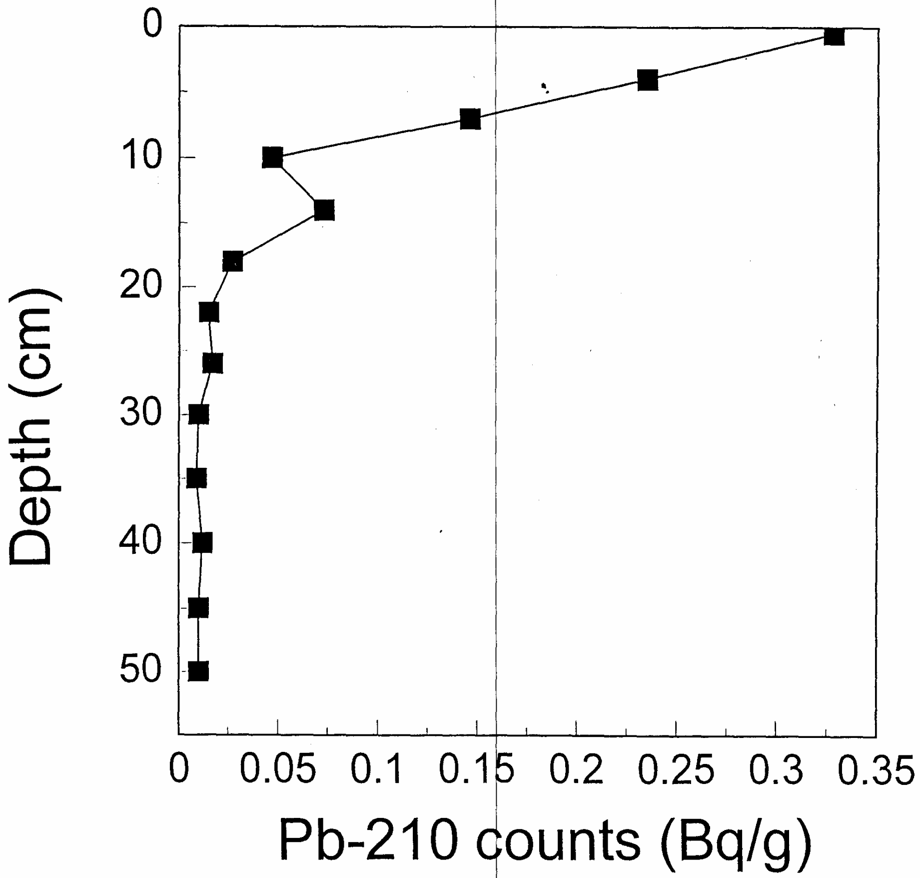
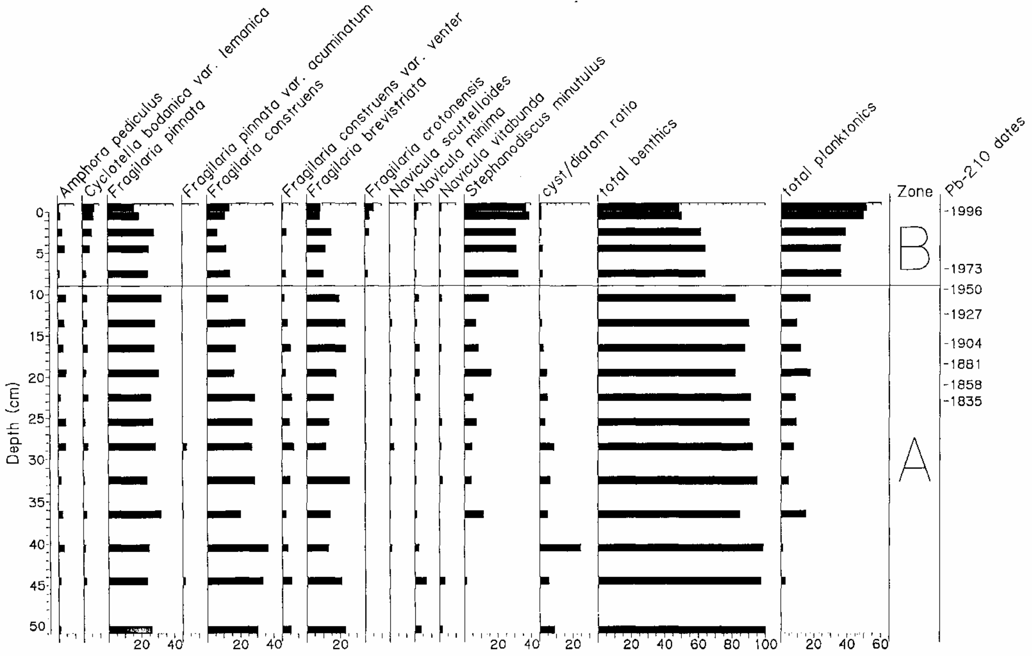

0
10
20
30
40
50
Depth (cm)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Pb-210 counts (Bq/g)

Fig 2



Amphora pediculus
Cyclotella bodanica var. lemanica
Fragilaria pinnata
Fragilaria pinnata var. acuminatum
Fragilaria construens
Fragilaria construens var. venter
Fragilaria brevistriata
Fragilaria crotonensis
Navicula scutelloides
Navicula minima
Navicula vitabunda
Stephanodiscus minutulus
cyst/diatom ratio
total benthics
total planktonics
Zone
Pb-210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
20
40
20
40
20
20
40
20
20
40
60
80
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A
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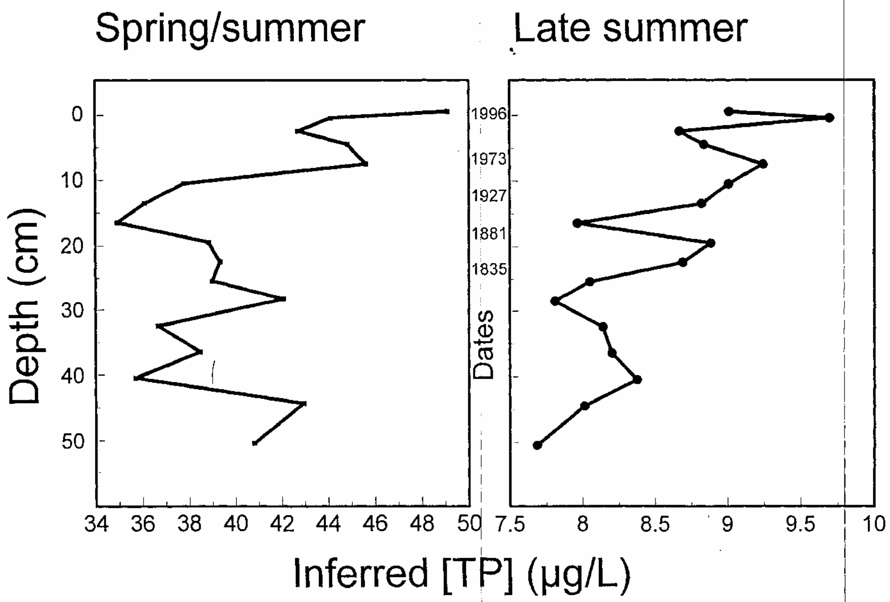
-1973
-1950
-1927
-1904
-1881
-1858
-1835

Fig. 2.


Spring/summer
Late summer
Depth (cm)
0
10
20
30
40
50
1996
1973
1927
1881
1835
Dates
34
36
38
40
42
44
46
48
50
7.5
8
8.5
9
9.5
10
Inferred [TP] (µg/L)