Synoptic Water Quality Study of Selected Halifax-Area Lakes: 2011 Results and Comparison with Previous Surveys

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SYNOPTIC WATER QUALITY SURVEY OF SELECTED HALIFAX-AREA LAKES: 2011 RESULTS AND COMPARISON WITH PREVIOUS SURVEYS

by

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ABSTRACT

Clement, P.M. and D.C. Gordon. 2019. Synoptic water quality survey of selected Halifax-area lakes: 2011 results and comparison with previous surveys. Can. Manuscr. Rep. Fish. Aquat. Sci. 3170: xi + 98 p.

The fourth synoptic survey of water quality in 51 Halifax-area lakes was conducted on 7 April 2011. Surface samples were collected by helicopter or small boat immediately after ice out when lakes were well mixed. Water quality variables measured included pH, major ions, nutrients, organic matter and trace elements. The results are compared to those of similar surveys previously conducted in 1980, 1991 and 2000. Statistically significant increases over the 31-year observation period were seen in conductivity, sodium, calcium, magnesium, potassium, chloride, alkalinity and nitrate. These increases were more pronounced in lakes with developed watersheds. The highest values for trophic state index (TSI) were found in Settle, Bissett and Rocky lakes indicating eutrophic (nutrient-rich) conditions. Except for pH, chloride, total nitrogen, zinc and arsenic in certain lakes, available guidelines suggest that the existing water quality poses no threat to aquatic life. The mean concentrations compare favourably with those observed in the water quality program conducted by the Halifax Regional Municipality between 2006 and 2011 with sampling in the spring, summer and fall. These synoptic surveys are only a part of the total spectrum of water quality monitoring programs that are needed to ensure the well being of Halifax-area lakes over the long term. Additional studies should have a more detailed spatial and temporal sampling design, cover all seasons of the year, include profiling the entire water column and measure other important variables including oxygen.

RÉSUMÉ

Clement, P.M. and D.C. Gordon. 2019. Synoptic water quality survey of selected Halifax-area lakes: 2011 results and comparison with previous surveys. Can. Manuscr. Rep. Fish. Aquat. Sci. 3170: xi + 98 p.

La quatrième analyse synoptique de la qualité de l'eau dans 51 lacs de la région d'Halifax a été réalisée le 7 avril 2011. Des échantillons de surface ont été prélevés par hélicoptère ou petite embarcation immédiatement après le dégel, lorsque les eaux des lacs sont bien mélangées. Parmi les variables de la qualité de l'eau mesurées, notons le pH, les ions majeurs, les éléments nutritifs, les matières organiques et les éléments traces. Les résultats sont comparés aux résultats d'analyses similaires réalisées en 1980, 1991 et 2000. Au cours de la période d'observation de 31 années, des hausses statistiquement significatives ont été constatées dans la conductivité, le sodium, le calcium, le magnésium, le potassium, le chlorure, l'alcalinité et les nitrates. Ces hausses étaient plus prononcées dans les lacs situés dans des bassins versants urbanisés. Les indices de l'état trophique les plus élevés ont été relevés dans les lacs Settle, Bissett et Rocky, ce qui révèle des conditions eutrophes (grande quantité de substances nutritives). Sauf pour ce qui est du pH, du chlorure, de l'azote total, du zinc et de l'arsenic dans certains lacs, les recommandations disponibles permettent de penser que la qualité de l'eau actuelle ne représente aucun risque pour la vie aquatique. Les concentrations moyennes se comparent favorablement à celles observées lors du programme de qualité de l'eau mené par la Municipalité régionale d'Halifax entre 2006 et 2011, pour lequel des échantillonnages ont été effectués au printemps, en été et à l'automne. Ces analyses synoptiques ne constituent qu'une partie du spectre total des programmes de surveillance de la qualité de l'eau, qui sont requis pour assurer la santé des lacs du secteur d'Halifax à long terme. Les études supplémentaires devraient porter sur des lacs précis, prévoir des échantillonnages plus détaillés dans l'espace et dans le temps, porter sur toutes les saisons, et viser le profilage de la colonne d'eau en entier et la mesure de variables importantes, y compris l'oxygène.

INTRODUCTION

The Halifax-area has over one thousand lakes which are invaluable resources for many uses including water supply, recreation and wildlife habitat. Urban development imposes various stresses on lakes and their watersheds, and careful environmental planning and management are necessary to maintain an acceptable level of water quality, both in built-up areas and regions undergoing development. Proper lake management requires an adequate scientific understanding of the natural processes that control lake properties, the types of pollutants being added and their origin, their concentrations in lake water and their impacts on important lake processes.

Due to the existence of numerous university and government environmental research laboratories, government environmental regulatory agencies and citizen environmental groups in the Halifax-area, a considerable number of scientific studies have been conducted on regional lakes (e.g. Gorham 1957, Ogden 1972, Watt et al. 1979, Castell et al. 1984, Mudroch and Clair 1985, Soil and Water Conservation Society of Metro Halifax 1991, Scott et al. 1991, Tropea et al. 2007, Stantec 2012, AECOM 2014, Ginn et al. 2015, Tarr and White 2015, Centre for Water Resource Studies 2016, Anderson et al. 2017, Poltarowicz 2017 and Dunnington et al. 2018). As a result, a substantial regional lake water quality dataset is being accumulated. Major pollutants identified to date include silt, road salt, nutrients and acid precipitation. Microorganisms from various sources have also become an important issue in some lakes. In addition the water quality of lakes is influenced by the bedrock geology of their watersheds and many receive considerable acid rock drainage, such as those in watersheds underlain by the Goldenville and Halifax groups (White and Goodwin 2011).

An exhaustive inventory of historical lake water quality data from a wide variety of sources has been compiled and is available on line (Mandaville 2018). This inventory, which includes on the order of one hundred Halifax-area lakes, also contains information on bathymetry, morphology, eutrophication status and modelling total phosphorous loadings as well as general information and references.

In 1980, the Department of Fisheries and Oceans (DFO) at the Bedford Institute of Oceanography undertook a project to measure the water quality of selected Halifax-area lakes. In partnership with Dalhousie University, the Nova Scotia Department of Environment and the federal Department of Environment (now Environment and Climate Change Canada), surface water samples were collected on a single day from 50 lakes in April 1980 using a helicopter and small boats (Gordon et al. 1981). These lakes were subjectively selected by the project leaders to cover a wide range of characteristics (e.g. location, size, watershed, degree of watershed development) and uses (e.g. water supply, recreation, wildlife habitat). These temperate lakes undergo a pronounced seasonal cycle. They are subject to potential stratification during the winter, when covered with ice, and in the summer when thermoclines can develop. However, in the early spring, immediately after the ice departs, lake water is generally well mixed from surface to bottom so that the properties measured in surface samples are representative of the entire lake volume. Standard water quality variables (e.g. pH, major ions, nutrients and organic matter) were measured and the resultant data were used to rank the lakes with regard to water quality (Gordon et al. 1981).

In order to begin exploring possible long-term trends in water quality, this survey was repeated in 1991 (Keizer et al. 1993). This second survey was again led by DFO and partners included the provincial Environmental Services Laboratory (Central Zone), Environment Canada, Nova Scotia Department of Environment, Dalhousie University and the Geological Survey of Canada. Two additional lakes were included and Secchi depth, aluminum, chlorophyll, colour, dissolved organic carbon and a wide range of trace elements were added to the variables measured.

Again led by DFO and in partnership with Environment Canada and the Geological Survey of Canada, a third survey was carried out in 2000 (Clement et al. 2007). The same lakes were sampled and the same variables were measured (except Secchi depth) as in 1991. The reports of these three surveys presented all the data and provided a general interpretation of the results, including an analysis of emerging long-term trends.

Due to the success of this program, it was decided to conduct a fourth synoptic lake survey in April 2011. This survey was again led by DFO and partners included the Nova Scotia Community College, the provincial Environmental Services Laboratory (Central Zone), the Halifax Regional Municipality, the Nova Scotia Department of Environment and the Geological Survey of Canada. This report presents the results of this most recent survey and compares them to those obtained in 1980, 1991 and 2000. It also includes an overview of the trace element data, which was not done in previous reports, and a more extensive discussion of the results. All data from the 2011 survey are presented in the appendices for those who wish to undertake further analysis and interpretation of this dataset. In addition, the results are compared with water quality data collected during the Halifax Regional Municipality Lakes Water Quality Monitoring Program which sampled the surface water of 68 lakes between 2006 to 2011 (Stantec 2012). This similar dataset provides the opportunity for evaluating the assumption that the data from these periodic synoptic surveys provide reasonable estimates of water quality that are useful for comparing lakes and examining long-term trends.

METHODS

SAMPLE COLLECTION

Surface water samples were collected at 86 locations in 51 lakes on 7 April, 2011 (Figure 1, Table 1). A subjective estimate of the degree of lake watershed development for all lakes sampled is given in Table 1. Samples were collected at the same locations as in the 1991 and 2000 surveys. As in the previous surveys, samples were collected a few days after ice left Fraser Lake, the last of the surveyed lakes to open. For quality assurance purposes, three replicate samples were collected from the same location in Lake Major, Lake Banook, Morris Lake and Maynard Lake. All sampling was completed in one day between 09:00 and 15:00.

Water samples were collected with 2 L high-density polyethylene bottles that had been previously washed with 1% HCl, rinsed twice, filled to soak, drained and left overturned to air dry. Most lakes were sampled using a helicopter. Sampling bottles were lowered from the hovering aircraft to a depth of approximately 30-50 cm using a weighted bottle holder (glug) attached to a rope (Figure 2). Smaller lakes in built-up areas were sampled within the same time period using small boats. Sampling bottles were fastened to a rod and also lowered to a depth of approximately 30-50 cm. In smaller lakes, single samples were taken near the centre while in larger lakes multiple samples were collected along the major axis. All sampling bottles were capped immediately after sample collection to avoid contamination. Each sampling team used labelled 2 L bottles, a mercury thermometer, the appropriate sampling device and log sheets on which date, time, sample number, identification number, location and temperature were recorded in the field.

SAMPLE PROCESSING

All samples were delivered within a few hours of collection to the Nova Scotia Community College (NSCC) Water Quality Laboratory at the Ivany Campus in Dartmouth and immediately refrigerated. Samples were shaken and processed within four hours of collection as follows:

- 100 mL subsamples were used to measure conductivity and pH at NSCC.
- 1100 mL subsamples were delivered refrigerated to the Environmental Services Laboratory (Central Zone) of the Nova Scotia Health Authority in the MacKenzie Building in Halifax for the analysis of numerous variables listed below.
- Duplicate 50 mL subsamples were frozen and delivered to the Department of Fisheries and Oceans at the Bedford Institute of Oceanography for inorganic nutrient analysis.
- 125 mL subsamples were filtered through pre-rinsed Durapore Sterivex 0.45 micron filters under light vacuum into pre-rinsed high-density polyethylene bottles, acidified with 1% HNO_3 and shipped to the Applied Geochemistry Laboratory of the Geological Survey of Canada in Ottawa for trace element analysis. This processing was done in a ‘clean’ laboratory to avoid airborne contamination.
- The remaining water (approximately 575 mL) was filtered through 0.45 micron GFF filters that were frozen in 95% acetone and delivered to the Department of Fisheries and Oceans at the Bedford Institute of Oceanography for determination of chlorophyll.

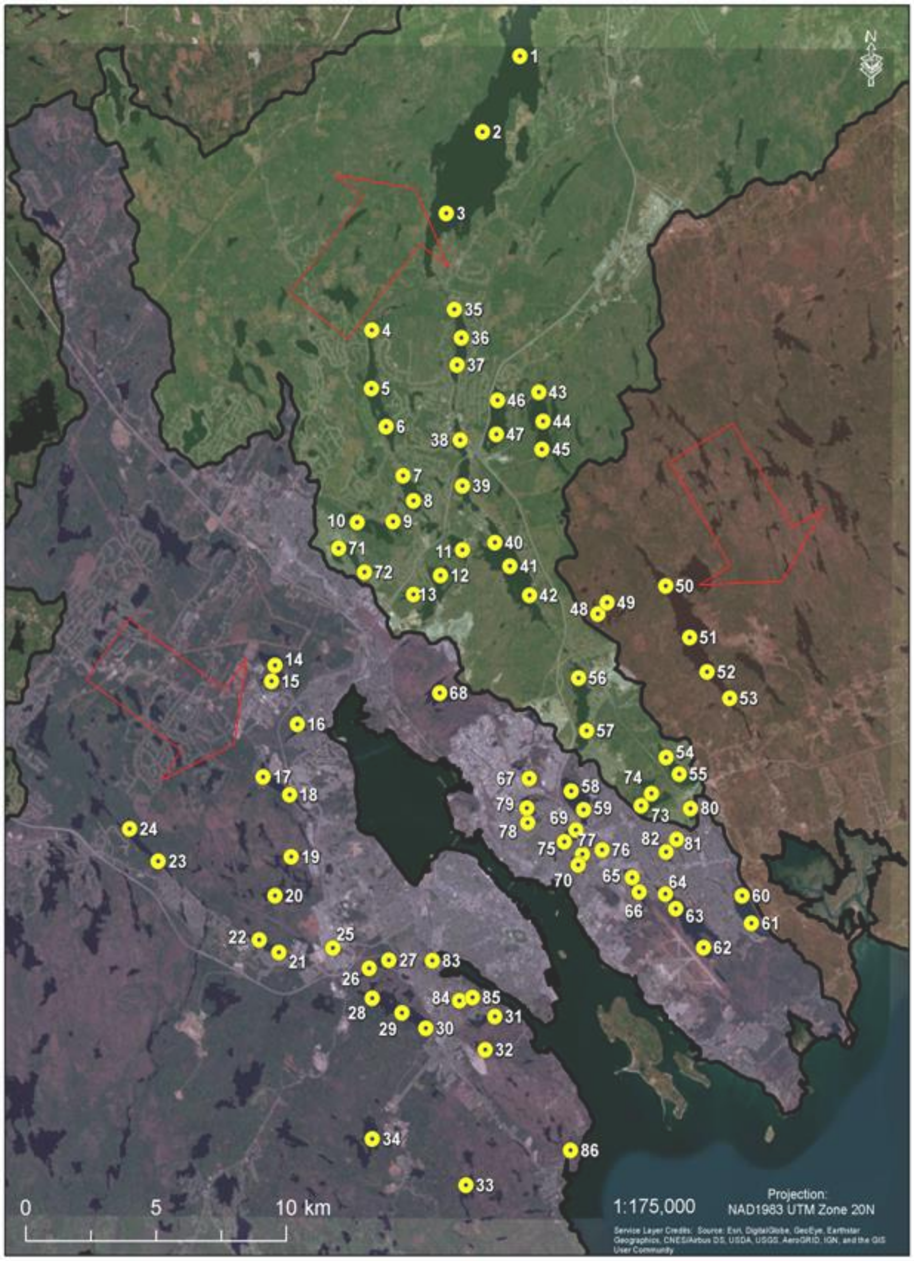

Figure 1. Location of sampling stations. Lakes are identified in Table 1. Also shown are the three primary watersheds: Sackville (grey), Shubenacadie (green) and Musquodoboit (red). The red arrows show the general direction of watershed drainage.

Table 1. Lakes sampled in the synoptic survey in 2011 and station numbers. Multiple numbers for a given lake indicate that samples were collected at more than one location. Three replicate samples were collected at one location in the four lakes indicated. The locations of lakes are shown in Figure 1. Lakes in blue are in relatively pristine watersheds while those in red are in heavily developed watersheds.

Station Number	Lake	Station Number	Lake
1-3	Grand Lake	50-53	Lake Major (replicates)
4-6	Kinsac Lake	54-55	Loon Lake
7-8	Third Lake	56-57	Lake Charles
9-10	Second Lake	58-59	Lake Micmac (replicates)
11	Powder Mill Lake	60-61	Bissett Lake
12-13	Rocky Lake	62-64	Morris Lake
14-15	Sandy Lake	65-66	Russell Lake
16	Paper Mill Lake	67	Frenchman Lake
17-18	Kearney Lake	68	Anderson Lake
19-20	Susie Lake	69-70	Lake Banook (replicates)
21-22	Governor Lake	71-72	First Lake
23-24	Fraser Lake	73	Lamont Lake
25	Bayers Lake	74	Topsail Lake
26	Second Chain Lake	75	Oathill Lake
27	First Chain Lake	76	Penhorn Lake
28-30	Long Lake	77	Maynard Lake (replicates)
31	Williams Lake	78	Little Albro Lake
32	Colbart Lake	79	Big Albro Lake
33	Parr Lake	80	Cranberry Lake
34	Spruce Hill Lake	81	Settle Lake
35-37	Lake Fletcher	82	Bell Lake
38-39	Lake Thomas	83	Chocolate Lake
40-42	Lake William	84	Whimsical Lake
43-45	Soldier Lake	85	Frog Pond
46-47	Miller Lake	86	Power Pond
48-49	Spider Lake		

Figure 2a. Sampling gear. Right to left: weighted bottle holder (glug) attached to a rope, 2-L sampling bottle and subsampling bottles used in the lab.

Figure 2b. Helicopter hovering to collect a water sample in Morris Lake by lowering the glug with a 2-L sampling bottle by rope to a depth of approximately 30-50 cm.

CHEMICAL ANALYSIS

The variables measured, units, detection limits and the responsible laboratories are listed in Table 2 along with the EPA methods used by the Environmental Services Laboratory.

Water Quality Laboratory

pH was measured within three hours of collection with an Orion Model pH meter calibrated with pH 4 and 7 buffers. Samples were stirred during measurement. Conductivity was also measured within three hours of collection with a WTW Model LF197 Profilab conductivity meter with a Model 013005 Duraprobe conductivity cell. The meter and probe were calibrated each day with two conductivity standards (12.9 µS/cm and 1413 µS/cm).

Environmental Services Laboratory

Conductivity, sodium, calcium, magnesium, potassium, aluminum, chloride, sulphate, alkalinity, total nitrogen, total phosphorus, dissolved organic carbon, colour and pH were determined using EPA standard methods for drinking water.

Department of Fisheries and Oceans

Duplicate samples were thawed and analyzed for dissolved ammonia, nitrate, phosphate and silica using a Technicon Autoanalyzer and a freshwater version of the methods described by Strain and Clement (1996). In the freshwater version, the wash and standards are 18.0 µMho water. Ammonia is a very labile compound which must be measured immediately before it undergoes chemical and/or biological transformations. Chlorophyll was measured within 24 hours with a calibrated Turner fluorometer.

Applied Geochemistry Laboratory

Samples were analyzed for rare earth elements, first-row transition elements, lead, cadmium and uranium. Samples were loaded onto a Dionex METPAC CC-1 column, eluted in 5 ml of 1N nitric acid and analyzed using Inductively Coupled Mass Spectrometry (ICP-MS).

DATA QUALITY AND ANALYSIS

Many of the chemicals measured are highly variable in both space and time in response to physical, chemical and biological factors. For some variables, natural concentrations are near the analytical limits of detection (Table 2) resulting in a large variance in replicate samples (Table 3). The variables with greatest variance were phosphate, silica, total phosphorus, chlorophyll and colour. The high variance for both phosphate and total phosphorus can be explained by their low concentrations, the complex chemistry of phosphorus in natural waters and their active role in biological processes.

In general, as in earlier surveys, there was good agreement between multiple samples taken from different locations in the larger lakes. Therefore, when two or more samples were collected from a lake, an average concentration was calculated.

Data for each variable are plotted in a horizontal bar graph with concentration across the x-axis (horizontal) and results for individual lakes in ascending order according to 2011 concentrations along the y-axis (vertical) (Figures 3-49). Data collected in 1980, 1991 and 2000 are plotted in different colours for comparison. These plots display the relative concentrations of each variable measured in the lakes sampled as well as any decadal changes.

All data collected in 2011 are presented in Appendices 1 and 2. Data from previous surveys are presented in earlier reports (Gordon et al. 1981, Keizer et al. 1993, Clement et al. 2007). All data can also be accessed online at https://atlanticdatastream.ca/. Statistical analyses were performed using the add-on statistical functions for Microsoft Excel 2003. Sampling station positions are presented in Appendix 3.

Table 2. Variables measured, units, detection limits and the responsible laboratory. NSCC is the Nova Scotia Community College Water Quality Laboratory, ESL is the Environmental Services Laboratory (Central Zone) of the Nova Scotia Health Authority, DFO is the Department of Fisheries and Oceans at the Bedford Institute of Oceanography and GSC is the Applied Geochemistry Laboratory of the Geological Survey of Canada in Ottawa. EPA methods can be found in the 20^{th} edition of the EPA Standard Methods Manual.

Variable	Units	Detection Limits	Responsible Laboratory	EPA Method
Temperature	°C	0.5	Field teams	
pH	Standard Units		NSCC	
Conductivity	µS/cm	1	NSCC/ESL	2120 C
Sodium (Na)	mg/L	0.5	ESL	3125
Calcium (Ca)	mg/L	0.5	ESL	3125
Magnesium (Mg)	mg/L	0.5	ESL	3125
Potassium (K)	mg/L	0.5	ESL	3125
Aluminum (Al)	mg/L	0.002	ESL/GSC	3125
Chloride (Cl)	mg/L	1	ESL	4110 B
Sulphate (SO_4)	mg SO_4/L	1	ESL	4110 B
Alkalinity	mg $CaCO_3$/L	-0.009	ESL	2320 B
Ammonia (NH_3)	mg N/L	0.002	DFO	
Nitrate (NO_3)	mg N/L	0.004	DFO	
Phosphate (PO_4)	mg P/L	0.0009	DFO	
Silica (SiO_2)	mg Si/L	0.006	DFO	
Total Nitrogen (TN)	mg N/L	0.02	ESL	4500-NB
Total Phosphorus (TP)	mg P/L	0.002	ESL	4500-PI
Chlorophyll	µg/L	1	DFO	
Diss. Organic Carbon (DOC)	mg C/L	0.5	ESL	5310 C
Colour	True Colour Units	5	ESL	
Trace Elements	µg/L		GSC	

Table 3. Mean concentrations and relative standard deviations (%RSD) of three replicate samples collected at the same location in four different lakes. To highlight excessive variability, instances where relative standard deviation (%RSD) exceeded 5% of the mean are shown in bold.

Variable	Units	Lake Banook Mean	%RSD	Lake Major Mean	%RSD	Maynard Lake Mean	%RSD	Morris Lake Mean	%RSD
pH	Std. Units	7.36	0.9	4.25	0.6	7.25	1.5	6.82	2.7
Conductivity	µS/cm	709	0.5	40	3.4	379	0.7	421	1.3
Sodium	mg/L	105.3	0.6	4.2	4.1	55.2	**5.2**	59.0	0.9
Calcium	mg/L	20.6	0.3	0.9	**6.0**	10.9	1.1	12.7	1.2
Magnesium	mg/L	2.2	0.0	0.5	0.0	1.7	3.5	1.6	0.0
Potassium	mg/L	1.7	0.0	0.5	0.0	1.2	0.0	1.3	4.3
Aluminum	mg/L	0.02	**5.9**	0.23	0.7	0.03	**6.4**	0.05	3.0
Chloride	mg/L	176	0.3	7	**5.8**	88	0.4	100	0.3
Sulphate	mg SO_4/L	19.5	1.1	3.2	1.8	11.1	0.9	12.1	2.9
Alkalinity	mg$CaCO_3$/L	24.3	0.4	-0.2	**89.6**	16.4	0.9	15.6	2.1
Ammonia	mg N/L	0.006	**27.4**	0.010	7.8	0.011	**20.9**	0.013	**16.4**
Nitrate	mg N/L	0.29	2.3	0.04	1.9	0.09	**7.4**	0.19	3.1
Phosphate	mg P/L	0.002	**34.4**	0.001	0.0	0.001	**14.4**	0.001	**14.9**
Silica	mg Si/L	0.53	**13.4**	0.15	**13.5**	0.42	**17.0**	0.36	**6.3**
Total N	mg N/L	0.43	2.7	0.16	3.7	0.25	4.7	0.35	1.6
Total P	mg P/L	0.003	**57.7**	0.002	**24.7**	0.004	**26.6**	0.005	0.0
Chlorophyll	µg/L	1.05	**24.1**	0.33	4.2	0.83	**7.9**	1.27	**75.7**
DOC	mg C/L	2.30	4.3	4.93	2.3	2.60	3.8	3.13	3.7
Colour	TCU	10.1	**8.2**	34.1	**11.4**	9.0	**6.8**	13.3	**6.2**

RESULTS

Before the data are presented, it must be emphasized that they should be interpreted with caution. The water quality variables measured can display strong spatial and temporal variability. The effects of spatial variability have been reduced in this study by collecting samples at the time of the spring turnover when lakes are vertically well-mixed and by collecting multiple samples in large lakes, but they have not been completely eliminated. Temporal variability can occur over the scales of hours, days and months. Major wind and precipitation events can have a pronounced effect on lake water quality. These effects have been reduced by collecting all samples within four hours on the same day. In addition, as is shown in the replicate sample data (Table 3), some variables are more difficult to measure precisely than others, especially those with concentrations near the limits of detection (e.g. ammonia, phosphate and total phosphorus). For these reasons, one must be cautious in comparing the concentrations of individual variables in different lakes or previous surveys for they are based on a limited number of samples and some of the apparent differences may not be significant. Concentrations can also be affected by changes in analytical methods, for example dissolved organic carbon, or the effects of storage on sensitive analytes such as ammonia and phosphate.

Before presenting and discussing the results of the survey, it should be noted that several natural and anthropogenic factors work in combination to affect lake water quality. The bedrock geology of watersheds plays an important role. The lakes sampled in this survey are underlain by three quite different general types of rock: the Goldenville Group (various metamorphic rocks of Cambrian age dominated by metasandstone), the Halifax Group (various metamorphic rocks of Cambro-Ordovician age dominated by slate) and the South Mountain Batholith (intrusive granitic rocks of Devonian age) (Donohoe 2005, White and Goodwin 2011, White et al. 2014). Anthropogenic factors include the removal of terrestrial vegetation in watersheds, development, mining and the addition of various pollutants through runoff and atmospheric deposition.

TEMPERATURE

Water temperature at the time of sampling ranged from 2.7 to 7.0 C (Figure 3). As in previous surveys, the higher temperatures were generally found in the shallower, smaller lakes (e.g. Whimsical, Little Albro, Penhorn, Cranberry) that lost their ice cover earlier and had more time to warm up. Temperature tended to be slightly lower than measured in earlier surveys.

pH

pH is a measure of the hydrogen ion concentration in water. A pH reading of 7 represents neutral conditions, while lower values indicate acid conditions and higher ones indicate alkaline conditions. Because of their bedrock geology, Halifax-area lakes are naturally acidic and few probably had pH values above 6 before European settlement.

pH is determined by the chemistry of all dissolved ions present but is controlled largely by the carbonate system.

Values of pH ranged from a low of 4.3 in Lake Major (most acidic) to a high of 7.4 in Lake Micmac (most alkaline) (Figure 4). The lowest values are generally found in lakes with relatively undisturbed watersheds (e.g. Major, Spruce Hill, Spider, Susie) or lakes such as First Chain and Second Chain that receive extensive acid rock drainage (Tarr and White 2015). The highest values are generally found in lakes with well-developed watersheds (e.g. Micmac, Banook, Maynard, Penhorn).

The overall range of pH was very similar in all four surveys (Figure 4). There was no consistent trend in mean pH over the 31-year observation period (Table 4) but values in 2000 and 2011 were higher than in 1980 (Table 5). pH in lake water is difficult to measure accurately and can vary markedly over a 24-hour period due to natural biological and chemical processes and so the limited pH data collected in these surveys are insufficient to discern long-term trends.

CONDUCTIVITY

Conductivity is a measure of the total dissolved ions in a water sample. All dissolved ions contribute but the most abundant cations and anions have the most influence. This is a relatively robust variable that is not greatly influenced by biogeochemical processes but can be influenced by human activities. Conductivity was determined by both the Nova Scotia Community College (NSCC) Water Quality Laboratory and the provincial Environmental Services Laboratory (ESL). Since there were some calibration issues with the NSCC measurements, only the ESL data are presented.

A wide range of conductivity readings is found in the Halifax-area lakes (Figure 5). The highest reading was 1600 μS/cm in Frenchman Lake while the lowest reading was 25 μS/cm in Spider Lake. As in previous surveys, the lakes with the lowest conductivity have relatively undisturbed watersheds (e.g. Spider, Major, Spruce Hill, Anderson). These natural levels reflect the dissolution of minerals from the weathering of bedrock and soil and the input of wind-blown sea salt. The highest values were found in lakes with well-developed watersheds (e.g. Frenchman, Whimsical, Micmac, Russell) and reflect the addition of anthropogenic contaminants such as road salt, lime and fertilizers. These chemicals are water-soluble and enter the lakes through storm water runoff. Atmospheric pollutants added to lakes by precipitation can also elevate conductivity readings.

With the exception of Second Chain Lake, conductivity in 2011 was higher in all lakes than in previous surveys (Figure 5). Overall, there has been a marked increase in mean conductivity of the lakes sampled over the 31-year observation period (Table 4) and the values in 2000 and 2011 were significantly higher than in 1980 (Table 5).

Theoretical conductivity was calculated from the concentrations of individual cations and anions using the equation described by Keizer et al. (1993) and was in excellent agreement with measured values in this survey ($r^2 = 0.989$). This strong correlation verifies the accuracy of the analyses for major cations and anions.

MAJOR CATIONS

Cations are dissolved ions that carry a positive charge. Major cations measured in this study were sodium, calcium, magnesium, potassium and aluminum. Observed concentrations are plotted in Figures 6-10.

The most abundant cation is sodium (Figure 6) and concentrations ranged from 0.4 to 200 mg/L. The second most abundant cation is calcium (Figure 7) and concentrations ranged from 0.5 to 26.5 mg/L. In comparison, concentrations of both magnesium and potassium were much lower (Figures 8 and 9) but similar. The relative ranking of lakes was very similar for each of these cations indicating that their ratios are relatively constant. As expected, there was also a very close correlation of the concentrations of cations with conductivity. As in previous surveys, the lowest concentrations were consistently found in lakes with relatively undeveloped watersheds (e.g. Spider, Major, Spruce Hill, Bell) while the highest were consistently found in lakes with relatively well-developed watersheds (e.g. Frenchman, Whimsical, Micmac, Russell). The lowest values observed reflect natural levels derived from the weathering of rock and atmospheric input of sea salts. Most of the lakes sampled appear to have concentrations above natural background levels.

Like conductivity, there has been a marked trend of increasing mean concentrations of sodium, calcium, magnesium and potassium in most of the 51 lakes sampled over the 31-year observation period (Table 4) and, with the exception of potassium, mean values in 2000 and 2011 were significantly higher than in 1980 (Table 5).

Aluminum concentrations were quite low and the relative ranking of lakes was much different from other cations (Figure 10). There was no evident relationship between concentrations and the degree of watershed development, indicating that human activities have little effect on aluminum concentrations. However, the bedrock geology of the watersheds clearly has an effect. For example, the high aluminum concentrations in First Chain, Second Chain, Susie and Governor lakes can be explained by the exposed sulphide-bearing slate bedrock in their watersheds which reduces their pH (Figure 4). The mean concentrations of aluminum for all lakes suggest a trend of decreasing value with time (Table 4) and the mean concentration in 2011 was significantly lower than in 1991 (Table 5). However, these results are influenced by some quite high concentrations observed in 1991 that may be suspect.

MAJOR ANIONS

Anions are dissolved ions which carry a negative charge. The major anions measured in this study were chloride, sulphate and those that contribute to alkalinity (e.g. carbonate, bicarbonate). Under natural conditions, the concentrations of anions in Halifax-area lakes are quite low and, like both conductivity and major cations, the major natural sources are the weathering of bedrock and atmospheric deposition.

A wide range of chloride, sulphate and alkalinity concentrations were found in Halifax-area lakes (Figures 11-13). Chloride ranged from 5 to 270 mg/L (Figure 11) while sulphate ranged from 2 to 44 mg/L (Figure 12). Alkalinity ranged from -0.7 to 26 mg/L and seven of the lakes sampled had little or no alkalinity (Figure 13). Chloride was by far the most abundant anion. As in previous surveys, the lowest concentrations consistently occurred in lakes with relatively undeveloped watersheds (e.g. Spider, Major, Spruce Hill, Bell) while the highest were consistently found in lakes with relatively well-developed watersheds (e.g. Frenchman, Whimsical, Micmac, Russell). Again, concentrations can also be influenced by the bedrock geology of their watersheds. Those lakes with the lowest concentrations of anions are also the lakes with the lowest values for conductivity and major cations. Most of the lakes sampled have anion concentrations that exceed natural background levels.

As expected, there is a very close relationship between alkalinity and pH. Lakes with high alkalinity (i.e. well-buffered) have high pH while lakes with no alkalinity (i.e. poorly-buffered) have low pH (Figures 4 and 13). The lakes in relatively undeveloped watersheds have little to no alkalinity. Therefore they have limited buffering capacity and are susceptible to acid rain and subsequent recovery. Lakes in well-developed watersheds do not suffer from acid precipitation because of the buffering capacity offered by other dissolved contaminants of human origin.

Mean chloride and alkalinity concentrations increased steadily over the 31-year observation period and concentrations in 1991, 2000 and 2011 were statistically significantly higher than in 1980 (Table 5). However, mean concentrations of sulphate showed no consistent trend although concentrations in 2000 and 2011 were significantly lower than in 1980 (Table 5).

NUTRIENTS

Nutrients are compounds of elements such as nitrogen, phosphorus and silicon that are required for the growth of aquatic plants. Under natural conditions, their concentrations are very low (less than 1 mg/L) so that they contribute little to conductivity. Natural sources include weathering of bedrock, decay of organic matter and atmospheric input. There are numerous anthropogenic sources which include sewage (primarily from septic systems), fertilizers and disturbance to land due to development. Four specific inorganic nutrients were measured in this study; ammonia, nitrate, phosphate and silica. In addition, total nitrogen and total phosphorus were measured which include both organic and inorganic forms.

Ammonia is difficult to measure accurately, especially after samples have been stored frozen for several weeks, and the results could be questionable. Observed concentrations were very low (Figure 14). There was no obvious correlation between concentrations and degree of lake watershed development as might be expected with winter accumulation due to low biological activity. The highest concentrations were found in Whimsical Lake which has a well-developed watershed. However, high concentrations were also found in Soldier and Miller lakes which have watersheds with relatively low levels of development. Surprisingly, urban lakes such as Banook, Micmac and Penhorn with well-developed watersheds had concentrations near the low end of the range. The high concentrations observed in some lakes in earlier surveys, especially 1980, are particularly suspicious.

Nitrate concentrations were substantially higher than ammonia (Figure 15). Generally speaking, the highest values of nitrate were found in lakes with well-developed watersheds (e.g. Oathill, Cranberry, Charles, Whimsical, Bissett). However, some urban lakes with well-developed watersheds had surprisingly low concentrations (e.g. Little Albro, Penhorn, Russell).

Phosphate concentrations were much lower than nitrate and close to the limits of detection (Figure 16). It was actually undetectable in approximately one third of the lakes sampled in 2011. Again, the highest values were found in lakes with well-developed watersheds (e.g. Settle, Rocky, Russell, Bissett, Oathill, Whimsical).

Silica concentrations were generally low and in the same range as nitrate (Figure 17) but there was no apparent relationship with the degree of watershed development. The frequent high concentrations observed in 1980 are suspicious.

Concentrations of total nitrogen and total phosphorus are plotted in Figures 18 and 19. Total nitrogen was much more abundant than total phosphorus and the highest concentrations of both tended to occur in lakes in well-developed watersheds. Total phosphorus, which was below the detection limit in six lakes sampled in 2011, is considered to be the limiting nutrient in the lakes sampled.

While concentrations fluctuated with time, there was no clear trend in the mean ammonia concentrations over the 31-year observation period (Table 4). The highest values occurred in 1980 and 2011 with lower values in 1991 and 2000 and the apparent significant differences are questionable (Table 5). However, mean nitrate concentrations have increased with time (Table 4) and values in 1991, 2000 and 2011 were significantly higher than in 1980 (Table 5). In contrast, no clear long-term trend was evident in the mean phosphate concentrations (Table 4). Although the mean concentration appeared to be significantly lower in 2011 (Table 5), this result is questionable since concentrations are very close to the limits of detection. Except for 2000, there appears to be a trend of increasing mean concentrations of total nitrogen over the 31-observation period (Table 4) with significantly higher values in 2011 compared to 1980 (Table 5). There was no detectable long-term trend in the mean concentration of total phosphorus (Table 4), perhaps because concentrations were again near the limits of detection.

ORGANIC MATTER

Chlorophyll is a pigment produced by plants which plays a critical role in photosynthesis and is a good indicator of phytoplankton biomass. Because of low nutrient concentrations, Halifax-area lakes before development in their watersheds had naturally low levels of phytoplankton biomass (and productivity) and therefore could be classified as oligotrophic. As nutrient enrichment takes place due to anthropogenic activity, chlorophyll concentrations can be expected to increase. Chlorophyll concentrations at the time of spring turnover are plotted in Figure 20. The highest concentrations occurred in Settle, Russell and Rocky lakes. Not surprisingly, these three lakes also had the highest concentrations of phosphate (Figure 16). As with phosphate, chlorophyll concentrations tended to be greater in lakes with well-developed watersheds. Chlorophyll concentrations can also be expected to increase substantially during the summer months.

Dissolved organic carbon (DOC) is a measure of all organic substances in water that pass though a filter. Under natural conditions, it includes humic materials as well as exudates from phytoplankton and rooted aquatic vegetation. DOC concentrations in Halifax-area lakes ranges from about 1 to 8 mg/L (Figure 21), levels that are thought to reflect natural conditions. There is no apparent relationship between DOC and degree of watershed development.

The yellow-brown colour found in many Halifax-area lakes is due primarily to the presence of naturally occurring dissolved humic materials. These large organic molecules are produced naturally by vegetation growing in lake watersheds, especially in acid bogs. Lake colour varied over a very large range from the very clear waters of First Chain, Bayers and Second Chain lakes to the highly coloured waters of Parr, Long, Power Pond, Spruce Hill, Fraser and Soldier lakes (Figure 22). The lakes with clear water generally have low pH and high aluminum concentrations that remove natural organic matter. As expected, there is a close relationship (r^2=0.932) between colour and DOC concentrations since these measurements include the same organic substances.

While mean concentrations fluctuated with time, there were no obvious trends in the mean concentrations of chlorophyll, DOC and colour over the 31-year observation period (Table 4). The DOC concentrations measured in 2000 and 2011 were generally higher in all lakes than in 1991. This difference might be due to changes in analytical methods but another explanation could be the demonstrated recovery of Halifax-area lakes from the effects of acid rain (Anderson et al. 2017).

TROPHIC STATE INDEX

Lakes can be classified on the basis of their general level of biological production. Oligotrophic (poorly-fed) lakes have clear water, are low in nutrients and plant biomass and maintain high oxygen levels year-round in deep water. Eutrophic (well-fed) lakes have turbid water, are high in nutrients and plant biomass and can have markedly reduced oxygen levels in deep water, especially during the summer months. Lakes with intermediate conditions are called mesotrophic. The progression from an oligotrophic to eutrophic condition in lakes is a natural process called eutrophication. Lakes in the Halifax-area are naturally oligotrophic but the addition of anthropogenic nutrients, especially phosphorus, can accelerate the eutrophication process.

The lakes in the Halifax-area are widely used for recreation and it is from this perspective that most people view water quality. Desirable attributes include clear water, clean shorelines and abundant native wildlife such as trout and loons. Such lakes generally fall into the oligotrophic category. As lakes become more enriched with nutrients, their attractiveness for recreation decreases as plant abundance increases and water clarity decreases. Therefore, it is important to monitor the trophic state of lakes so that corrective action can be taken if nutrient conditions become, or are predicted to become, unacceptable.

The trophic state of a given lake can be estimated by the trophic state index (TSI) (Carlson 1977). This numerical index ranges on a scale of 0 to 100 and each major division (10, 20, 30, etc.) represents a doubling in algal biomass. It can be calculated from chlorophyll, total phosphorus or transparency data. The resulting indices can be different and Carlson (1977) argues that chlorophyll is the best variable to use in most lakes as a trophic state indicator. There is no exact relationship of TSI to the broad subjective categories of trophic state (i.e. oligotrophic, mesotrophic, eutrophic) but in general the higher the index the more eutrophic a given lake is likely to be and the lower the index the more oligotrophic. TSI can be a valuable tool for lake management as well as for scientific investigations where an objective standard of trophic state is needed.

The TSI values for all lakes calculated using the chlorophyll data are plotted in Figure 23. Values ranged from a high of 58 in Settle Lake to a low of 5 in Chocolate Lake. This low value in Chocolate Lake is surprising since a large portion of its watershed is developed. Russell and Rocky lakes also had values in excess of 50. As expected, the lakes with highest values generally have well-developed watersheds and a higher probability of nutrient enrichment. Other lakes with low TSI values included Lake Major, Paper Mill Lake and Kearney Lake. Similar to chlorophyll, there was no apparent trend in the mean TSI for all lakes from 1991 to 2011 (Table 4). Lakes with the highest TSI values did not show marked increases with time. It is interesting to note that Lake Micmac has experienced a marked increased in rooted aquatic vegetation in recent years but had a relatively low value of TSI (Figure 23). Presumably this is because the TSI values are calculated using springtime chlorophyll concentrations from the middle of the lake and are not accurate predictors of summertime conditions in near shore sediments.

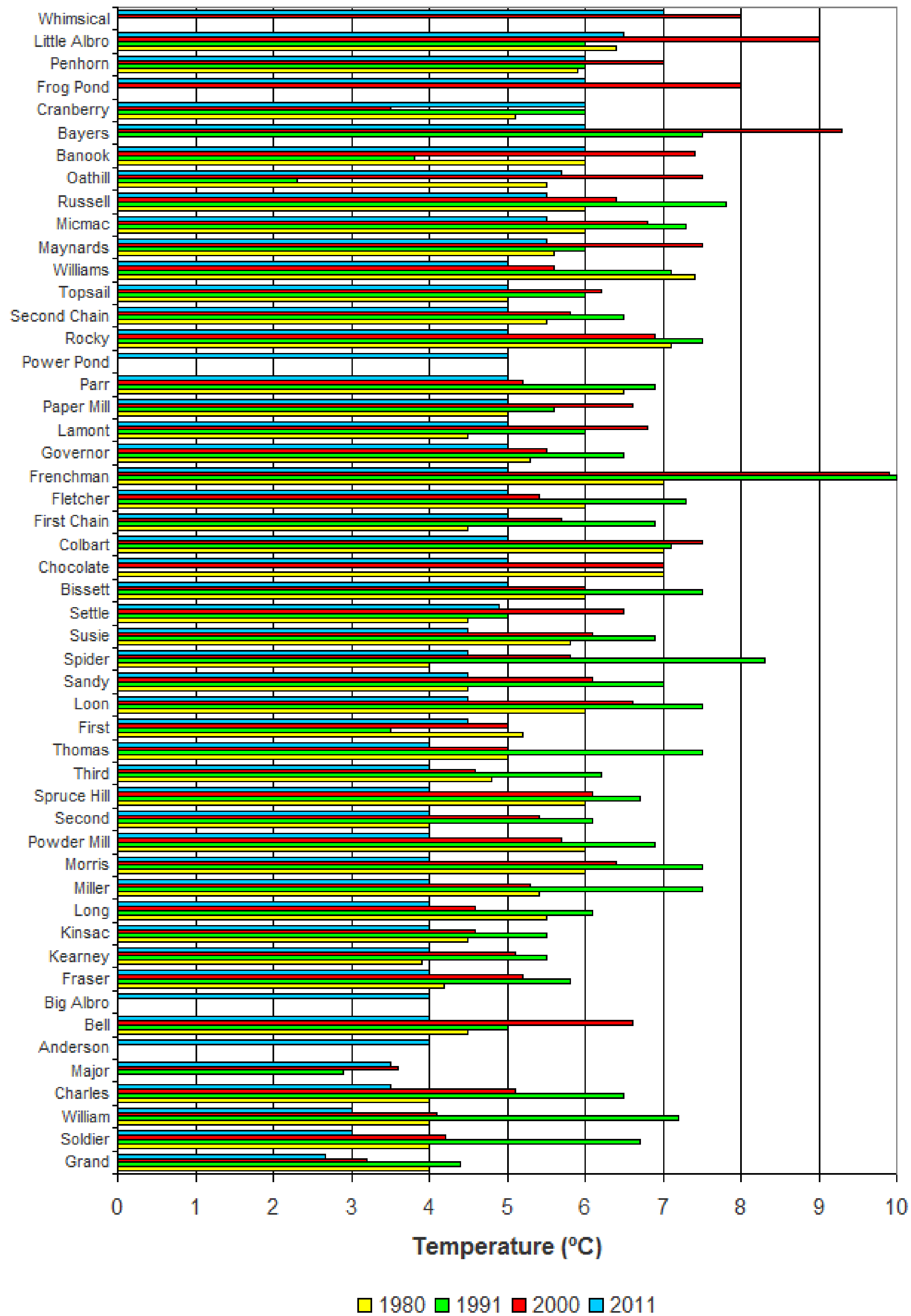

Figure 3. Temperature of water samples at the time of collection.

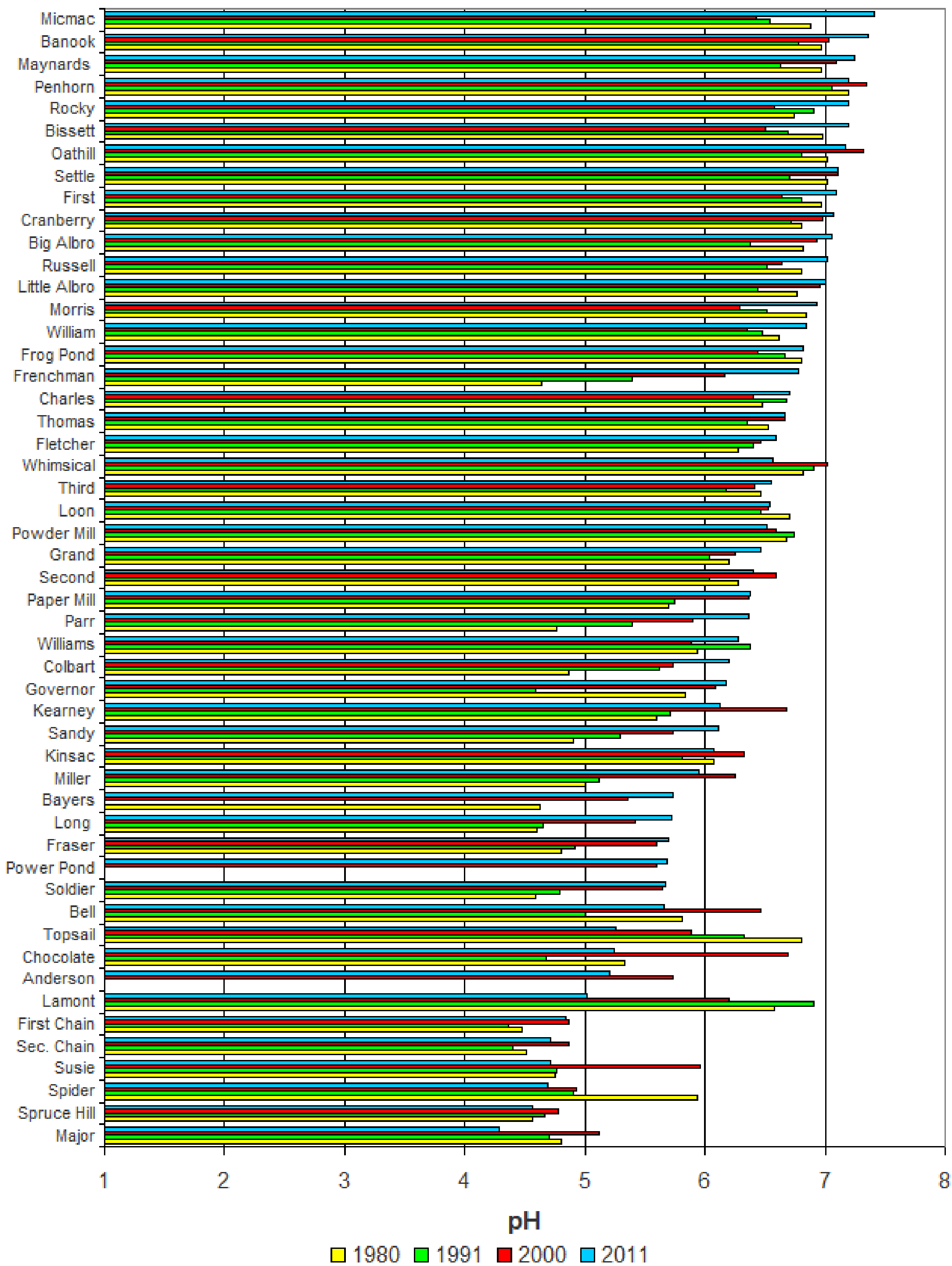

Figure 4. pH. The CCME water quality guideline is 6.6 to 9.0.

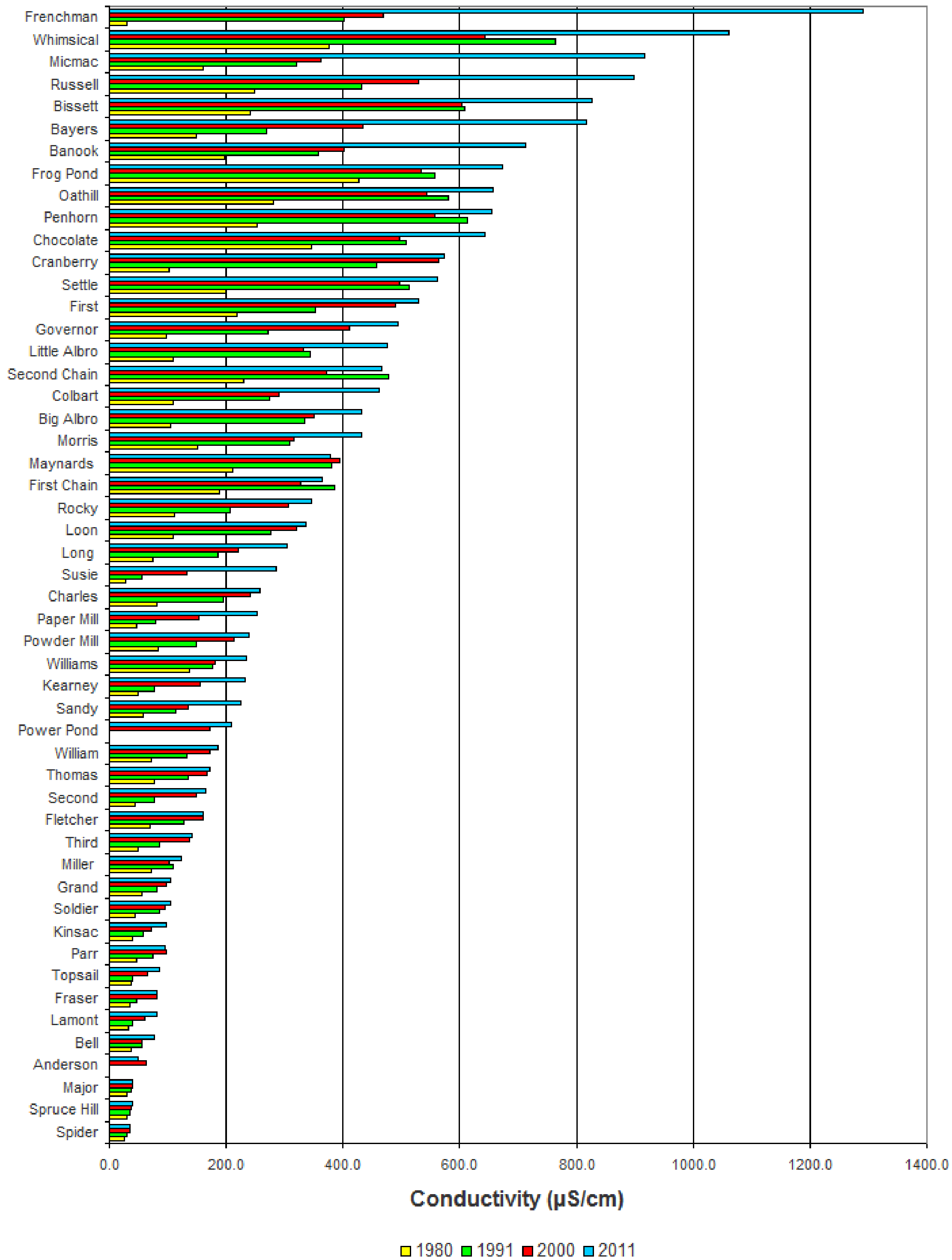

Figure 5. Conductivity readings as measured by the Environmental Services Laboratory.

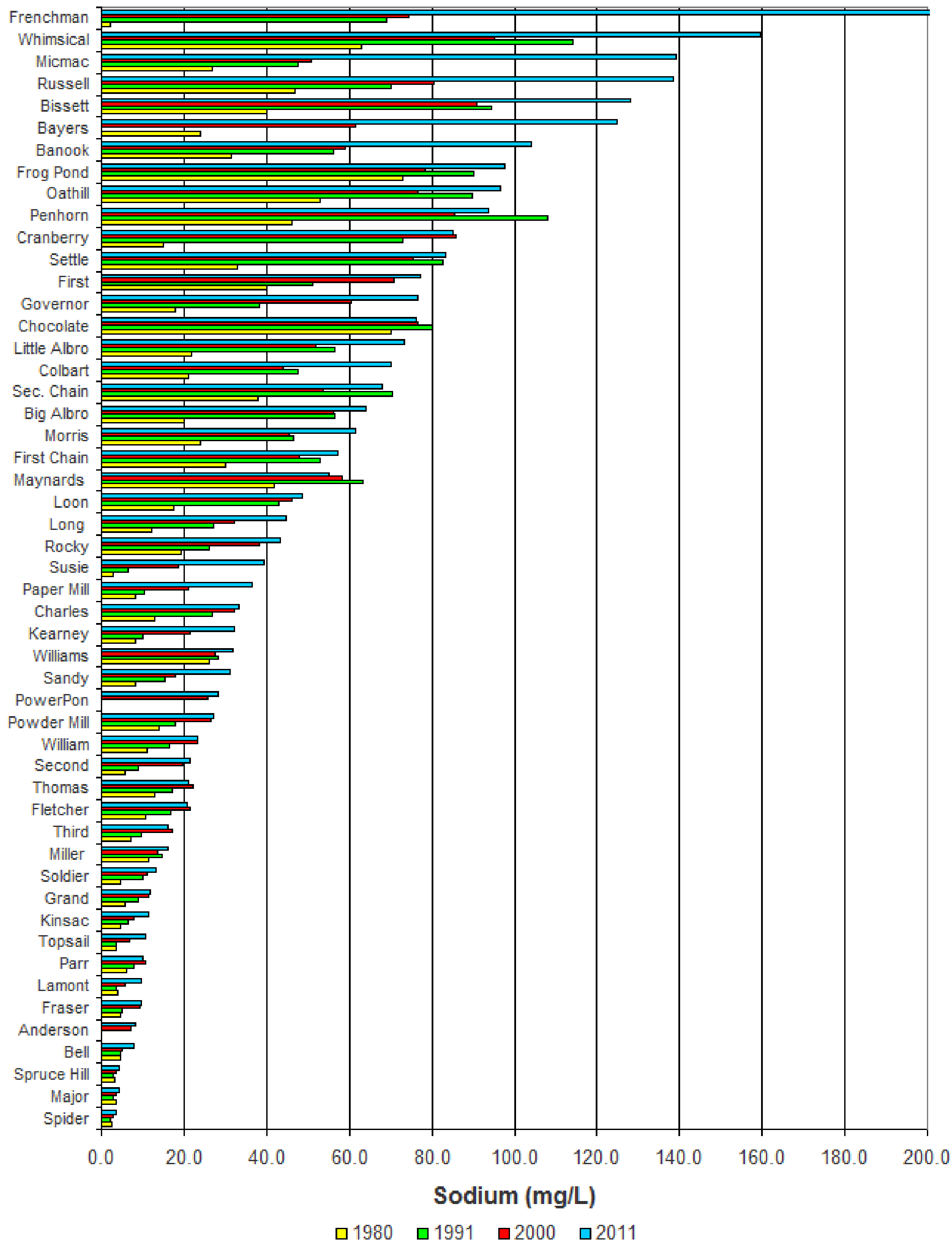

Figure 6. Sodium concentrations.

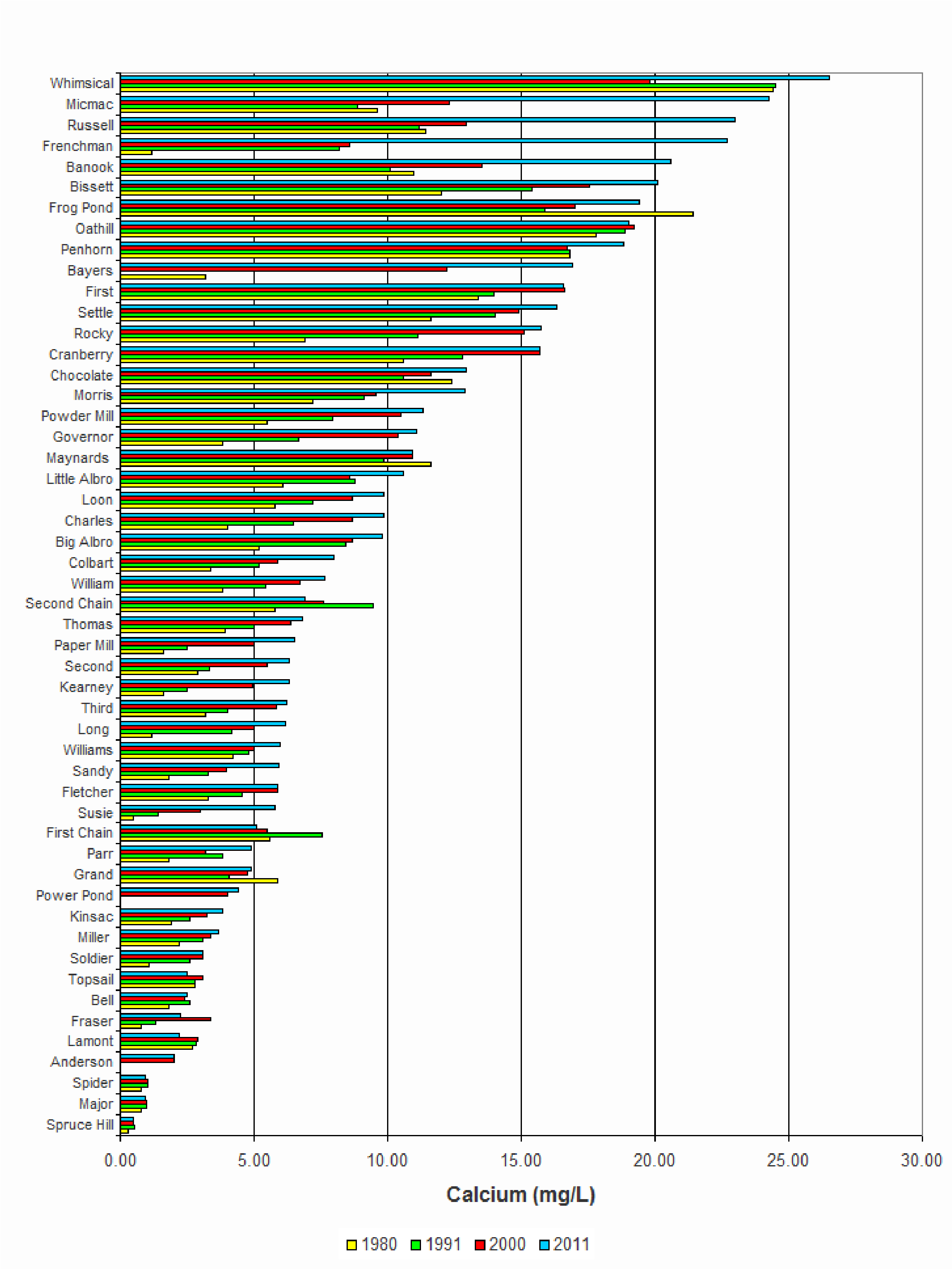

Figure 7. Calcium concentrations.

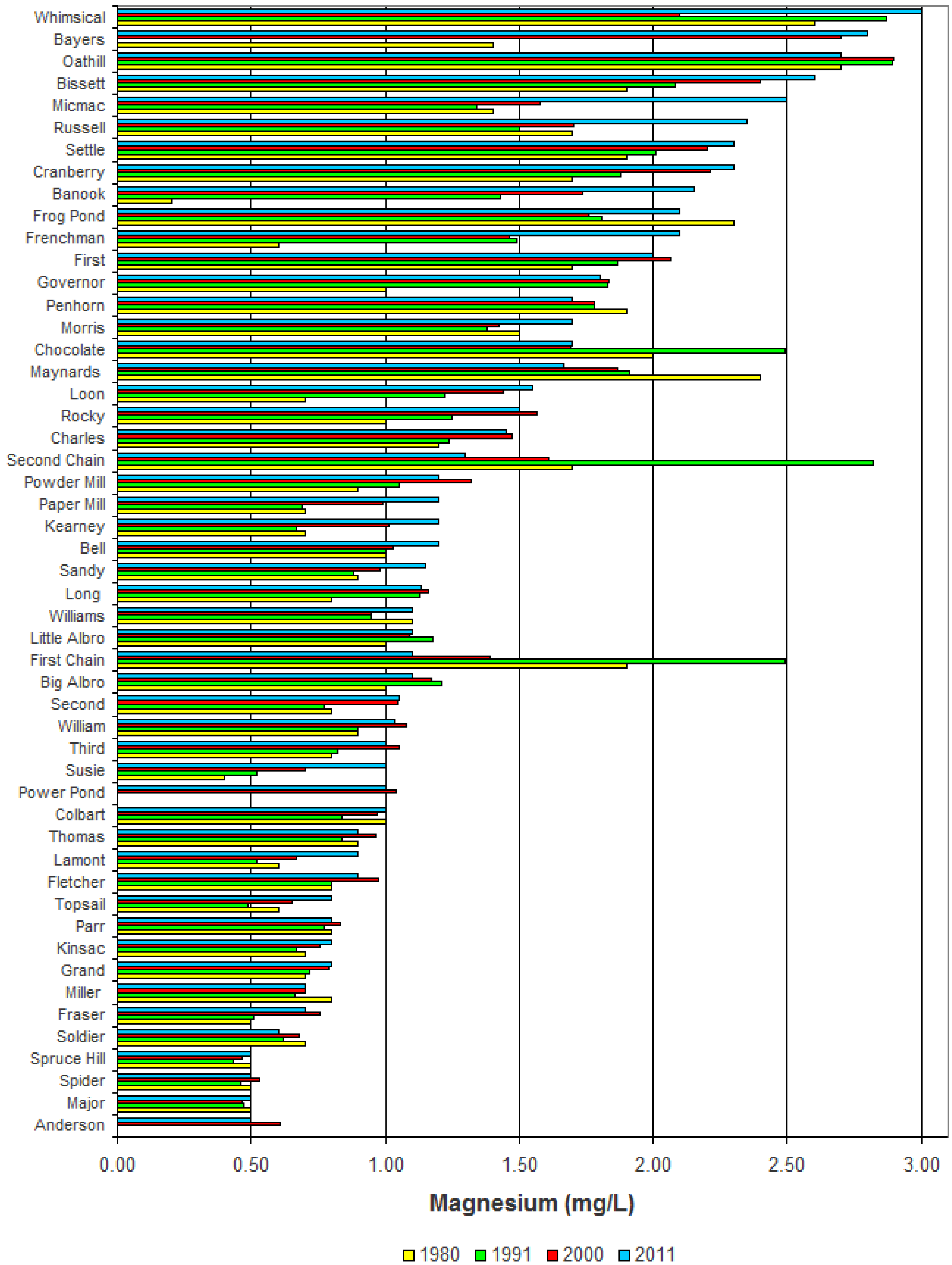

Figure 8. Magnesium concentrations.

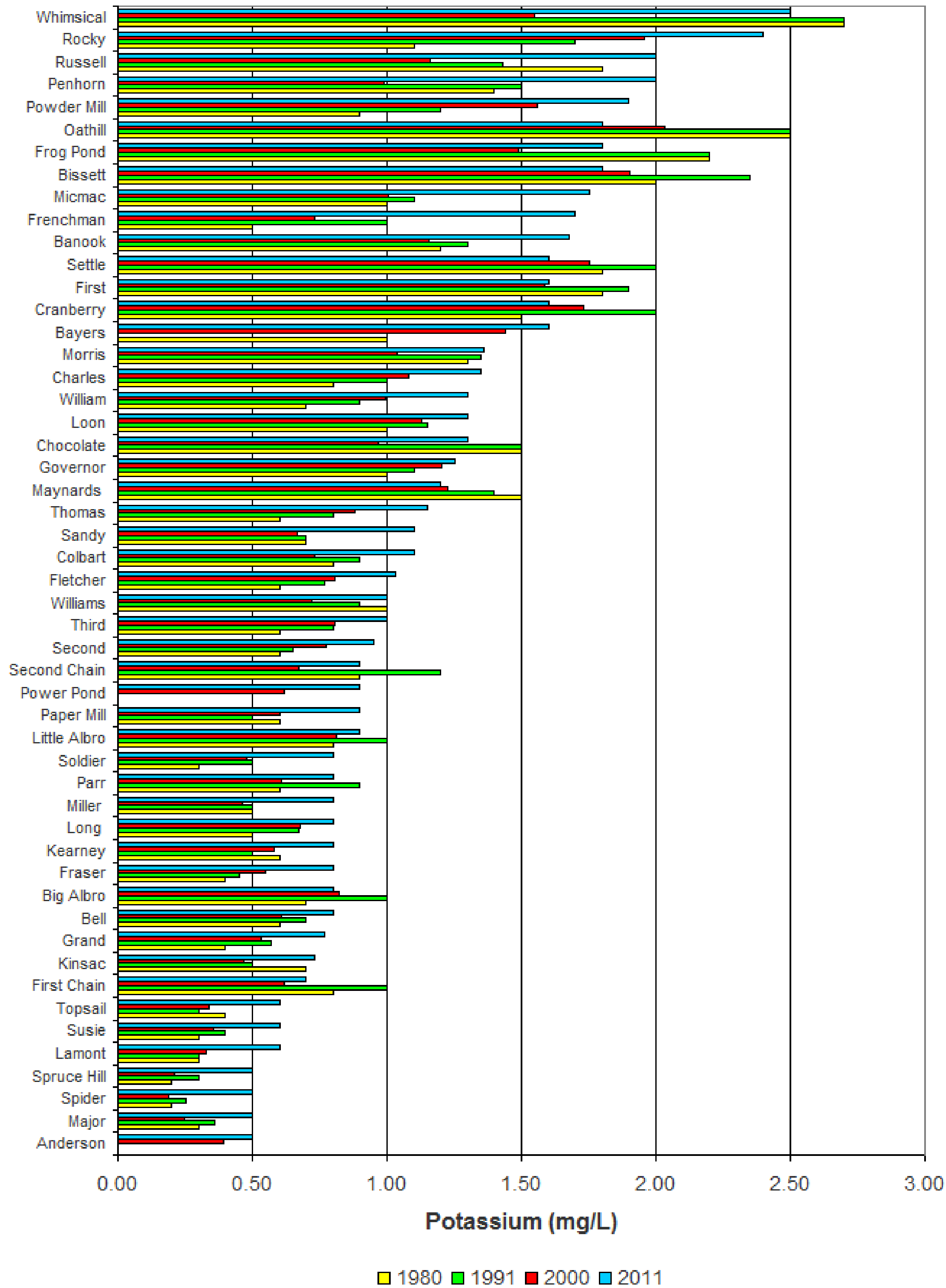

Figure 9. Potassium concentrations.

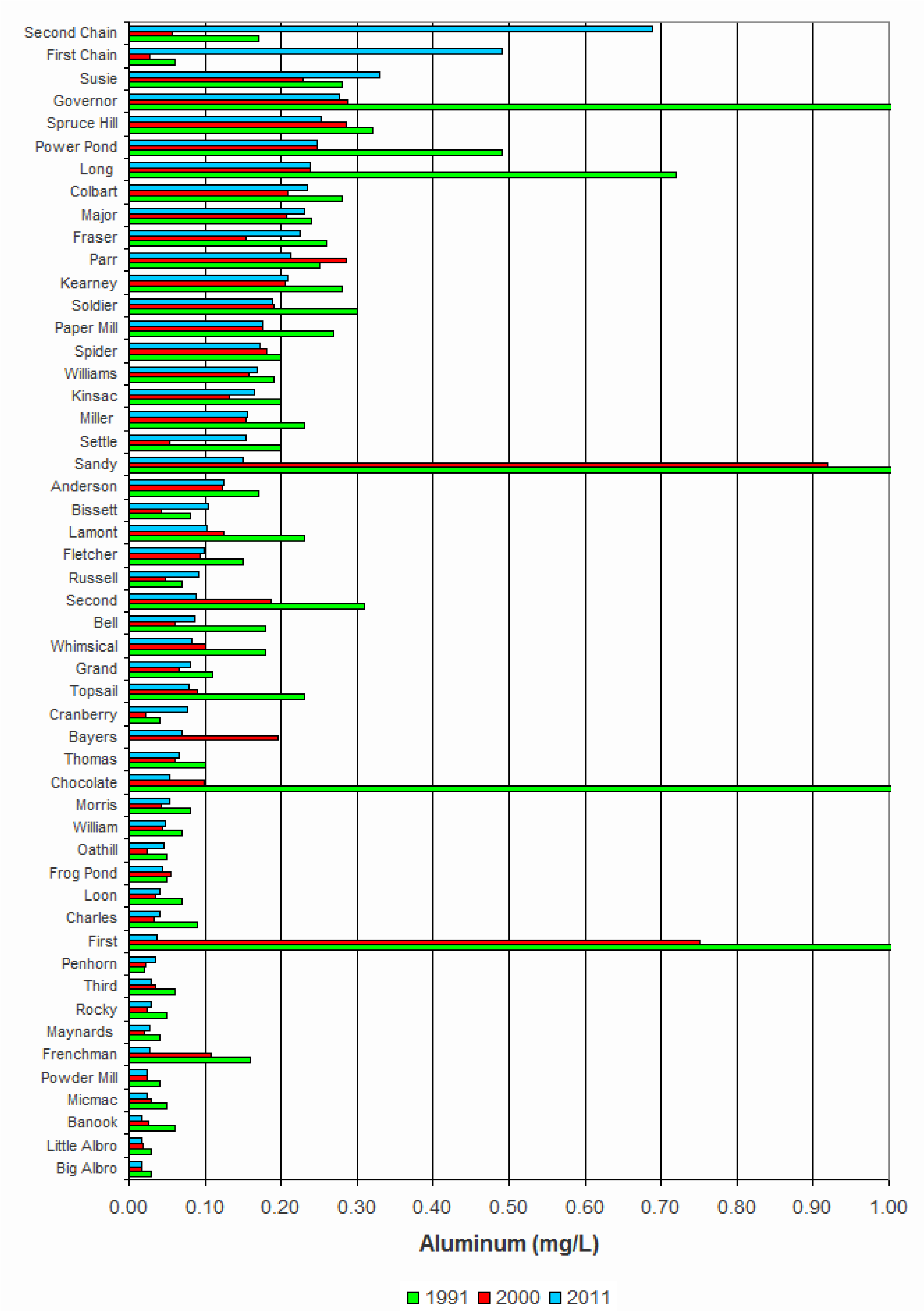

Figure 10. Aluminum concentrations as measured by the Environmental Services Laboratory.

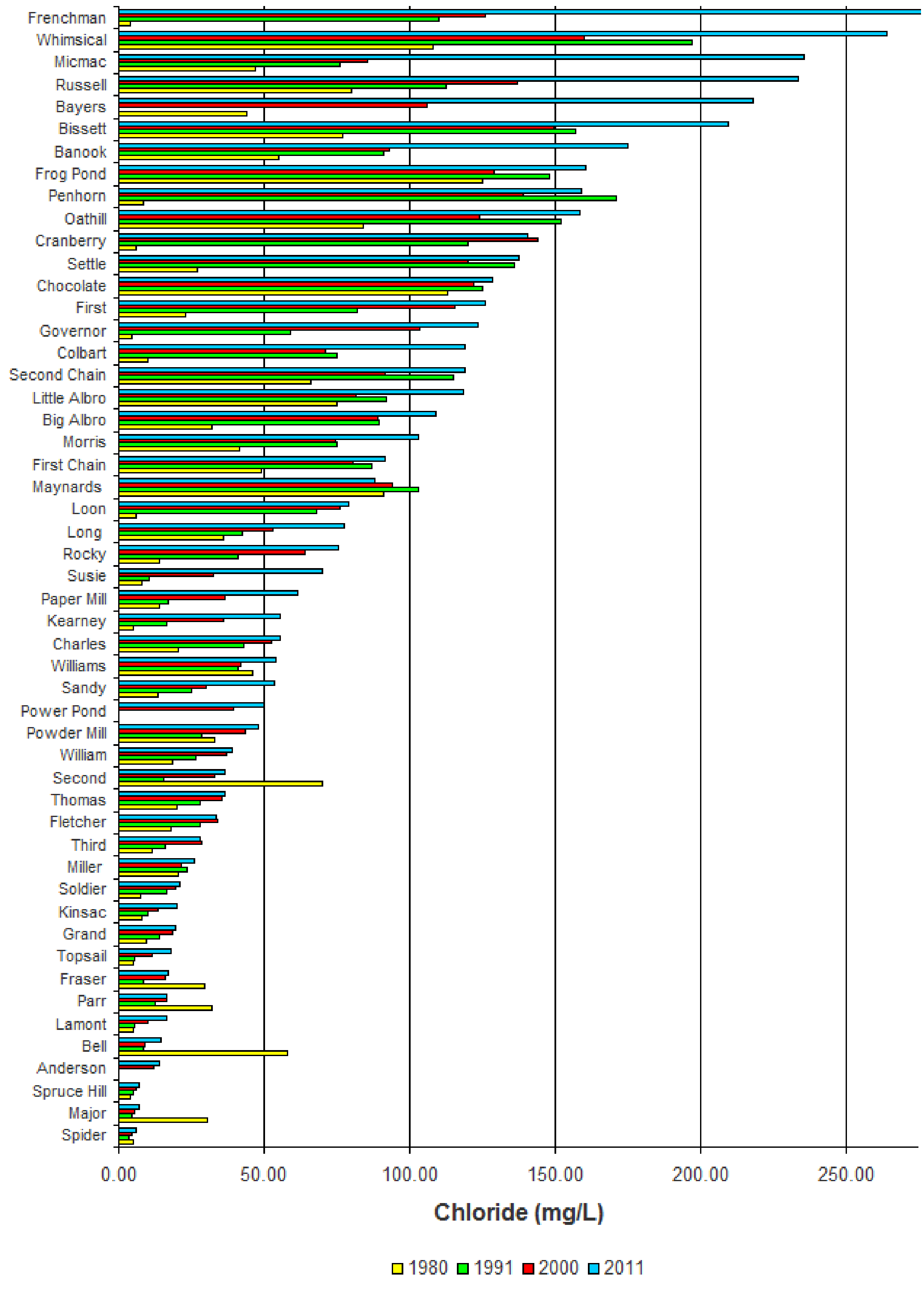

Figure 11. Chloride concentrations. The CCME water quality guideline is 120 mg/L.

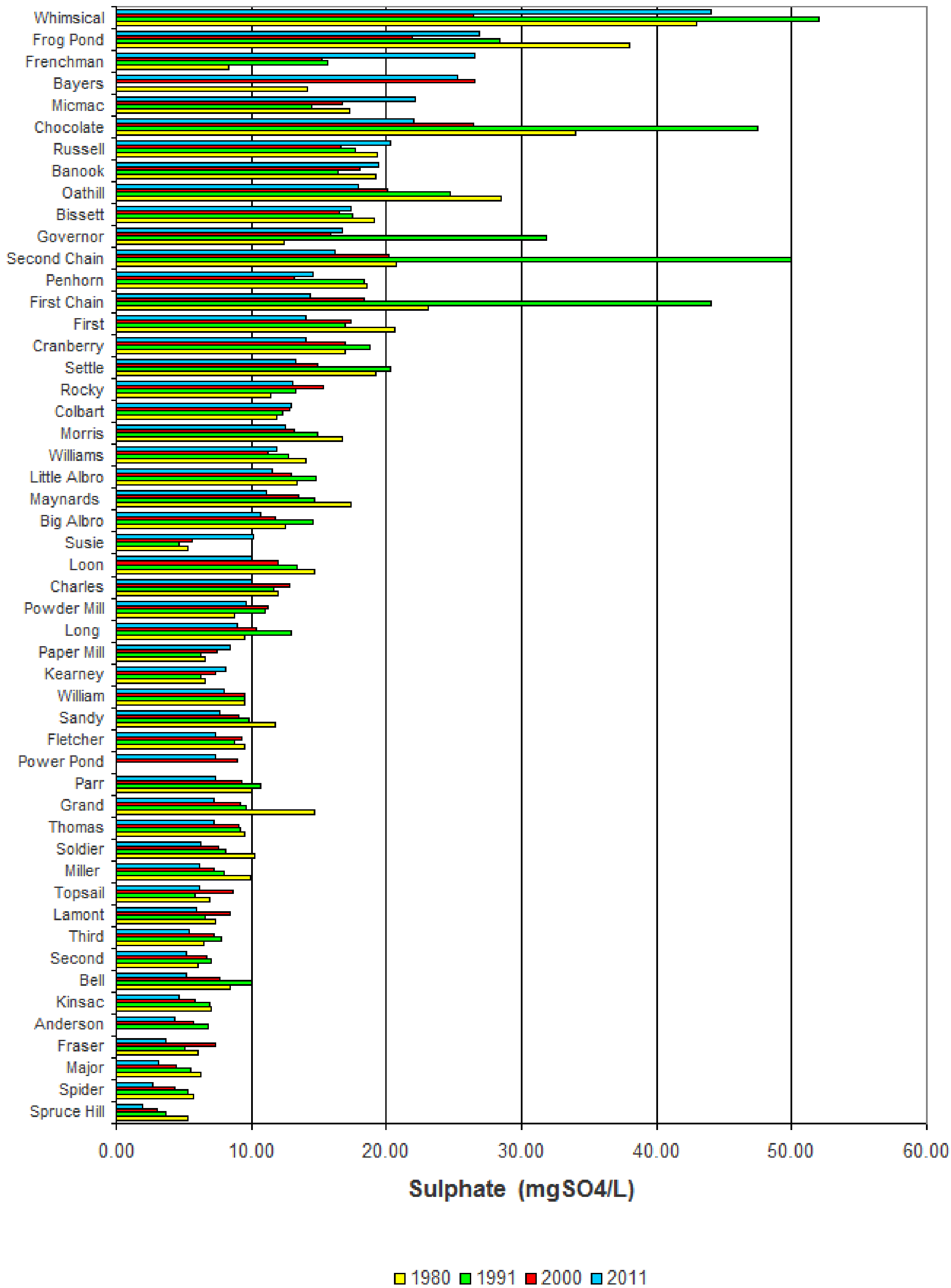

Figure 12. Sulphate concentrations.

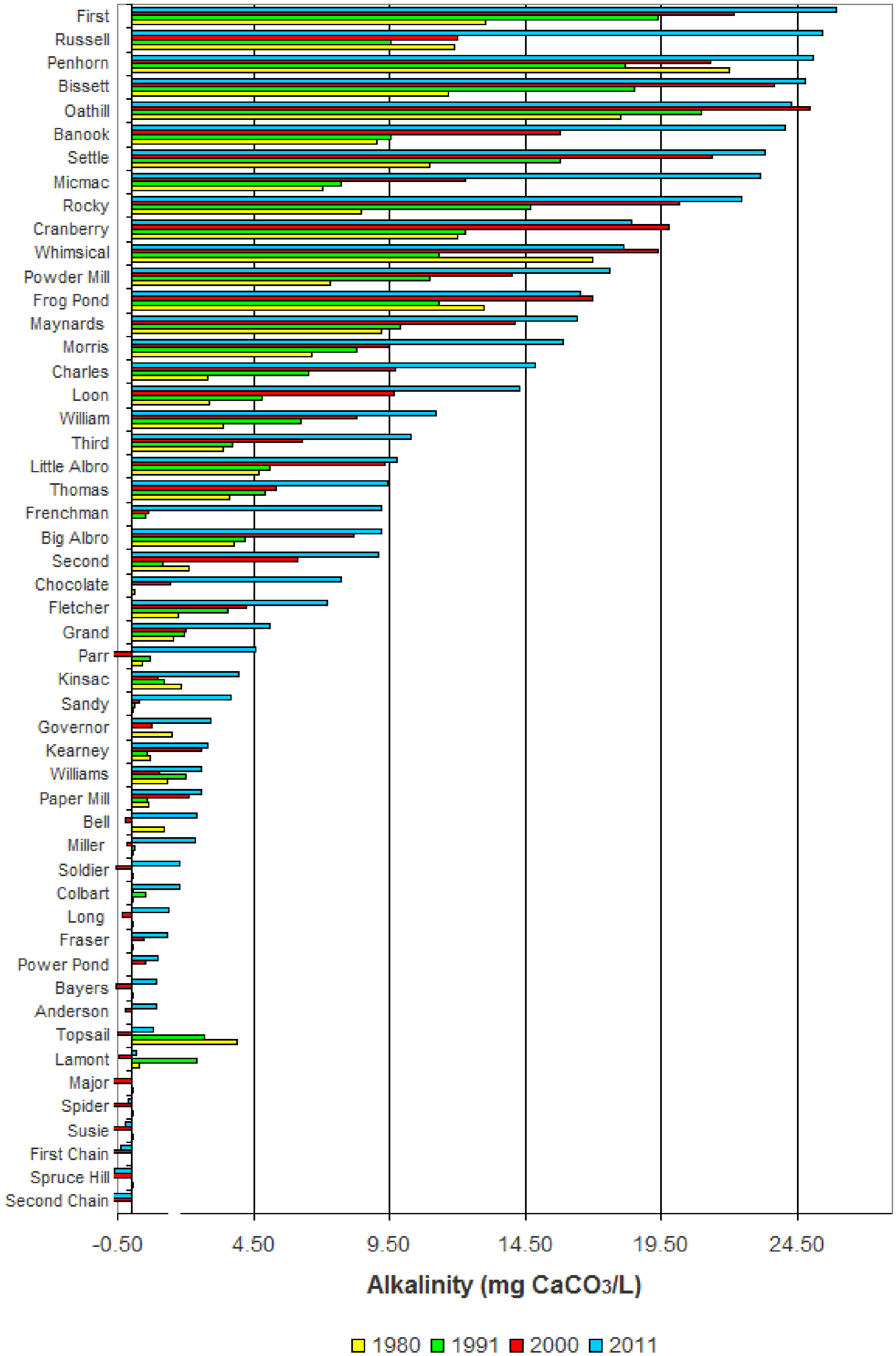

Figure 13. Alkalinity concentrations.

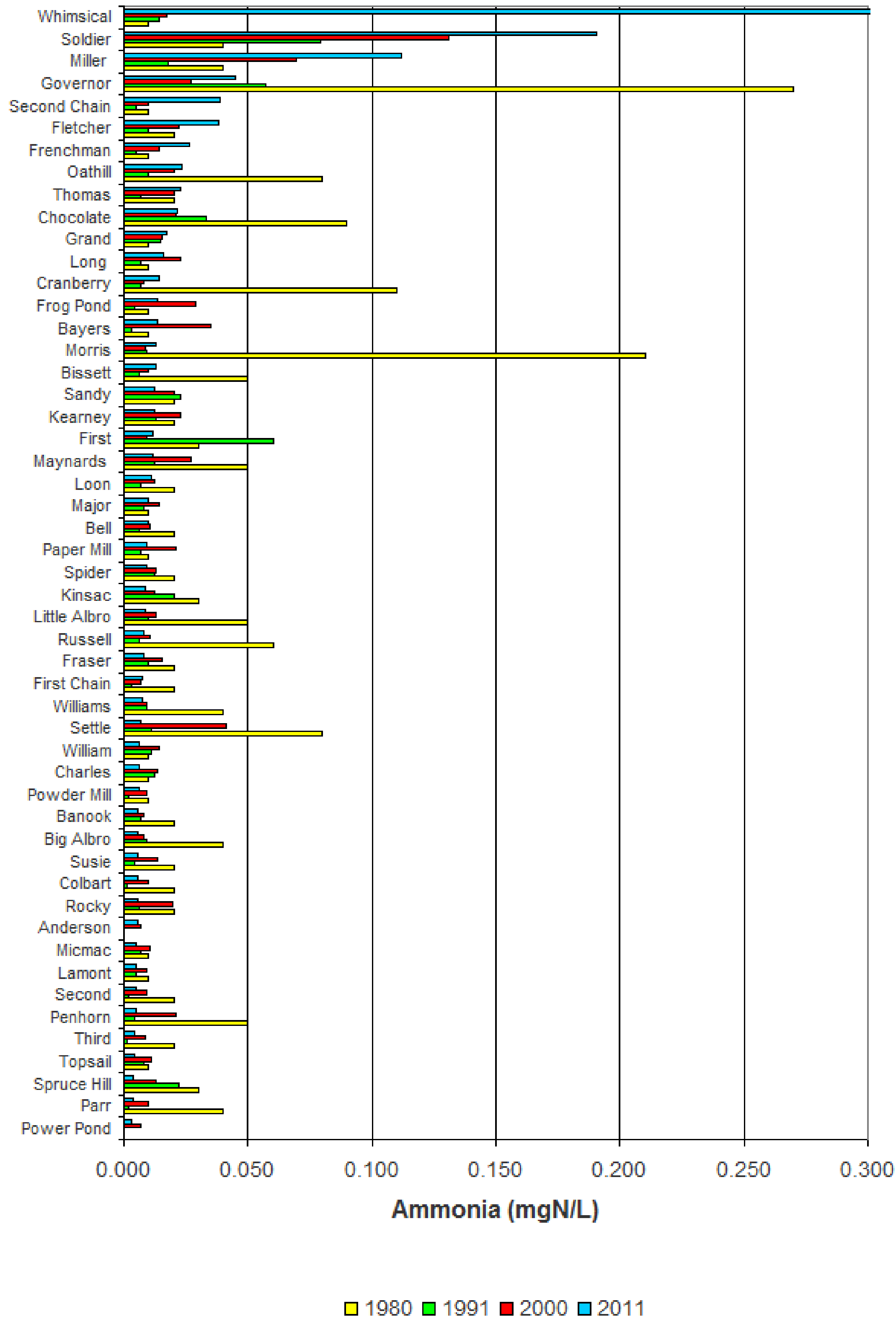

Figure 14. Ammonia concentrations.

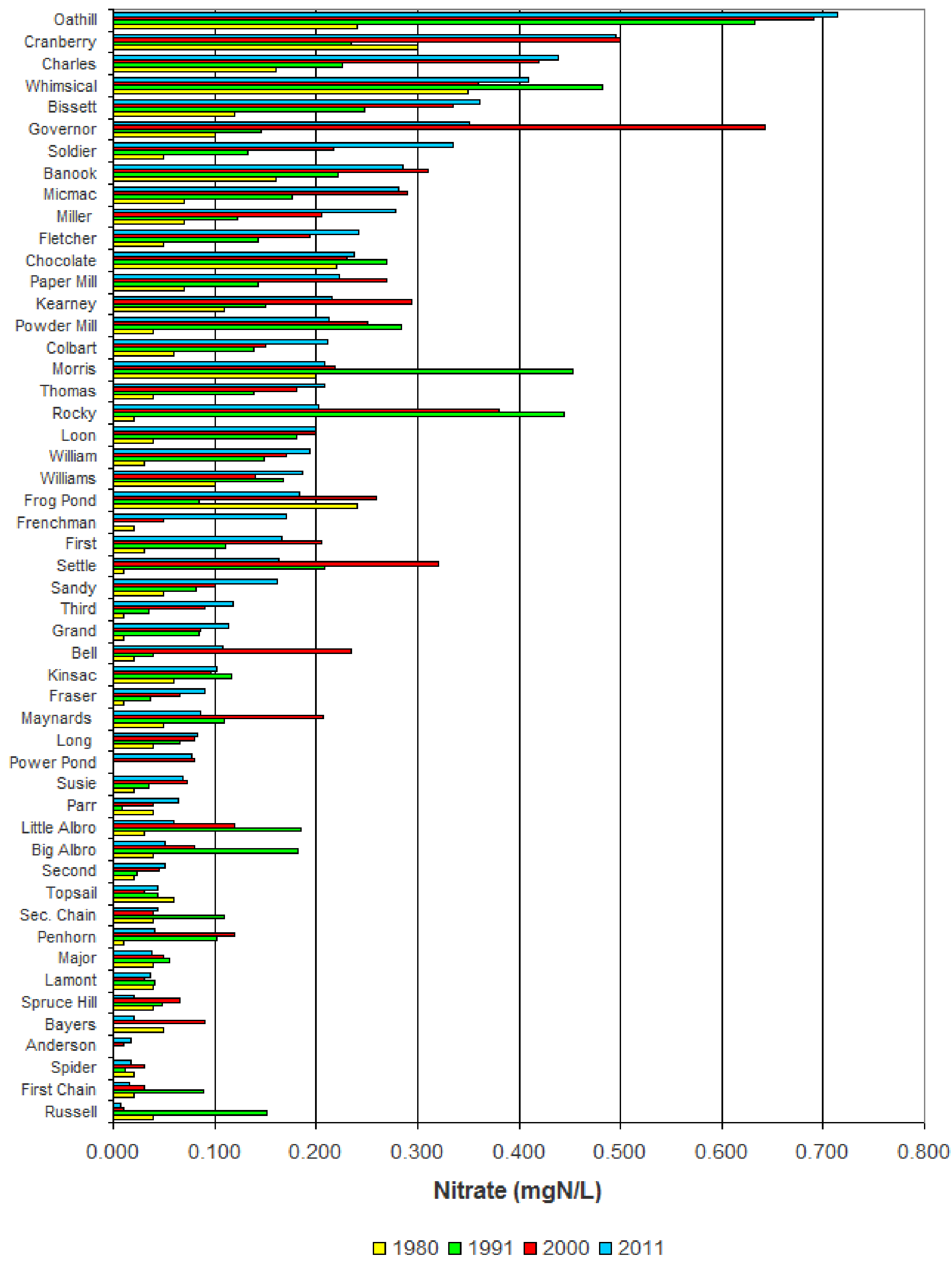

Figure 15. Nitrate concentrations.

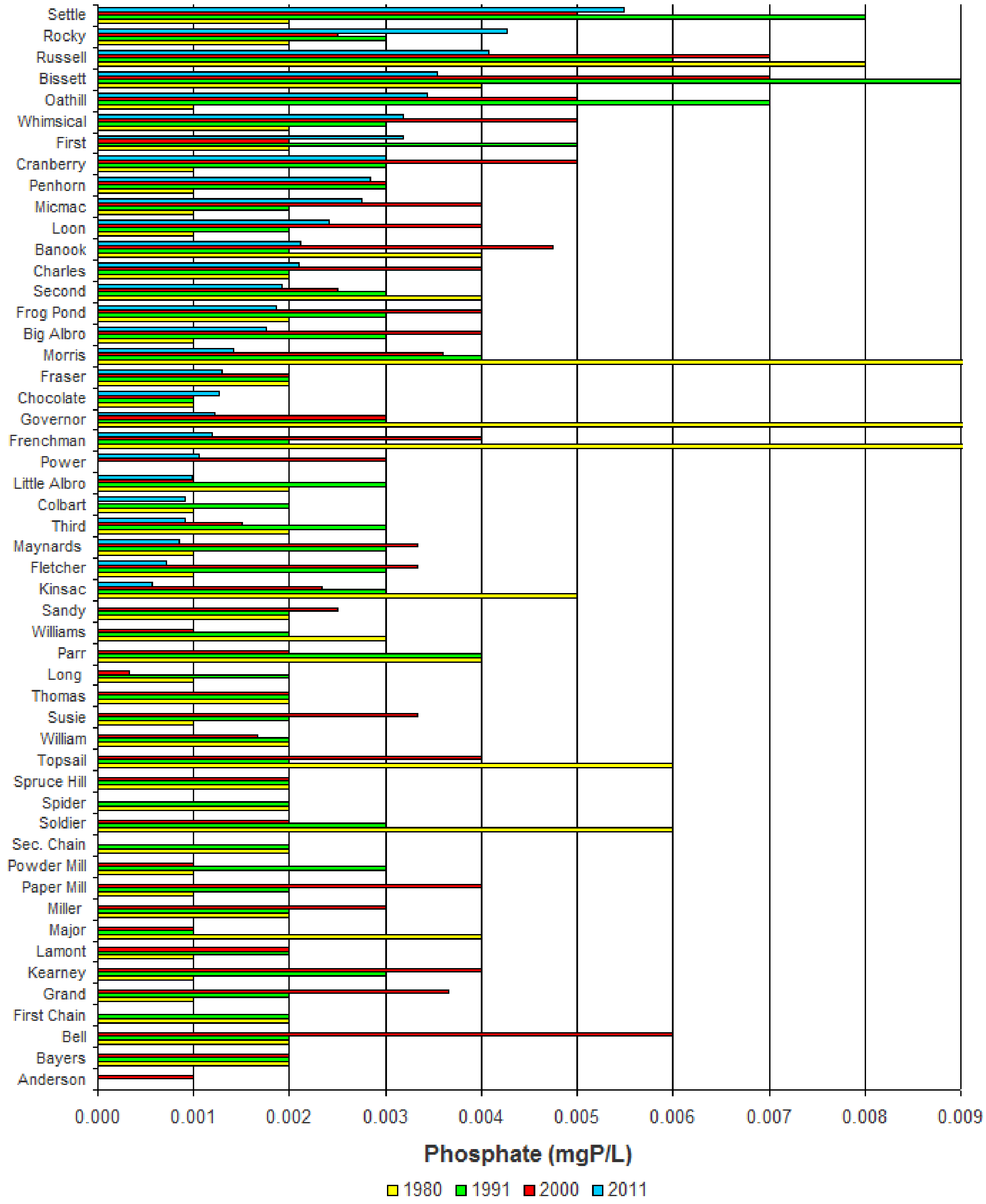

Figure 16. Phosphate concentrations.

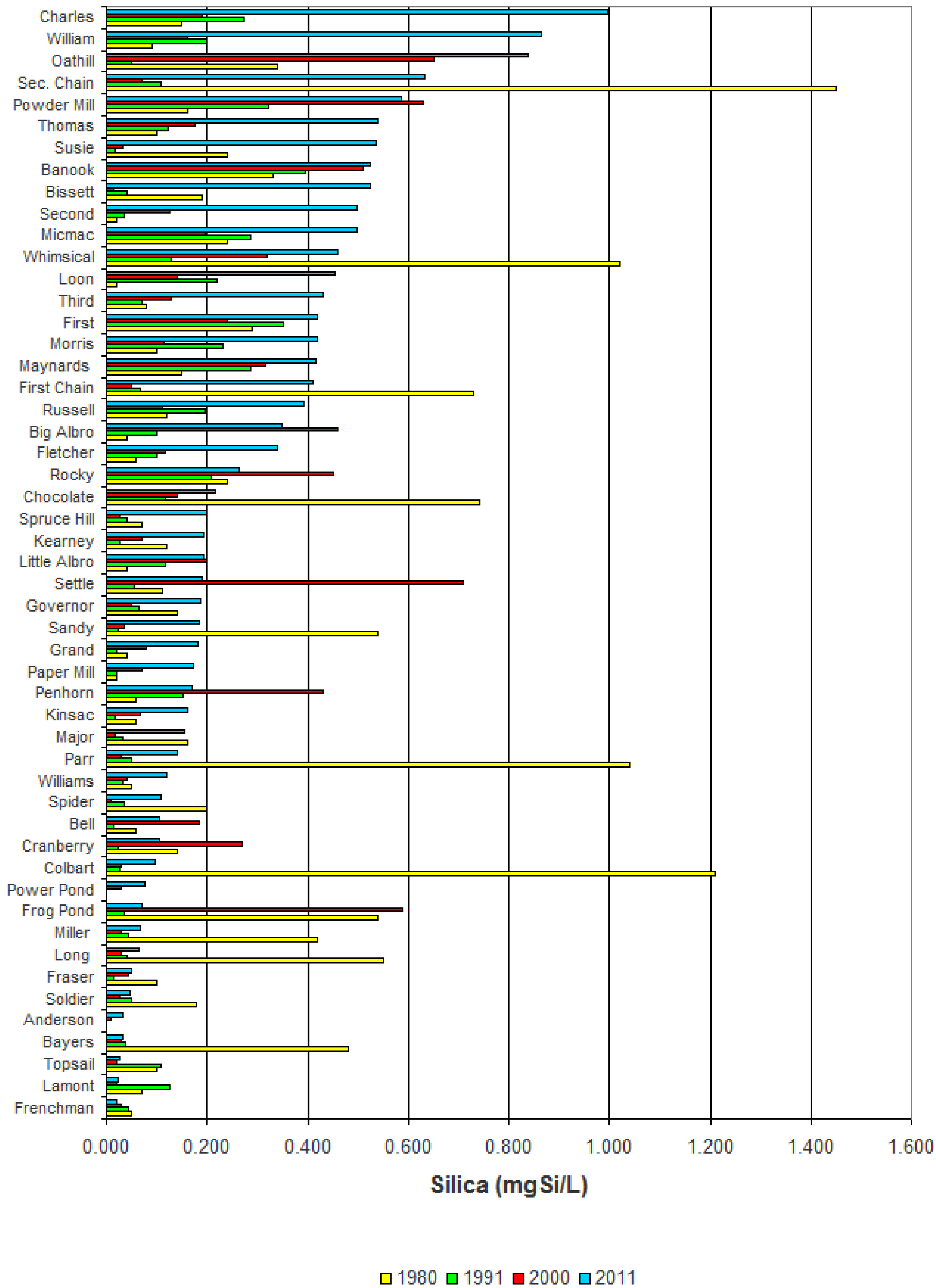

Figure 17. Silica concentrations.

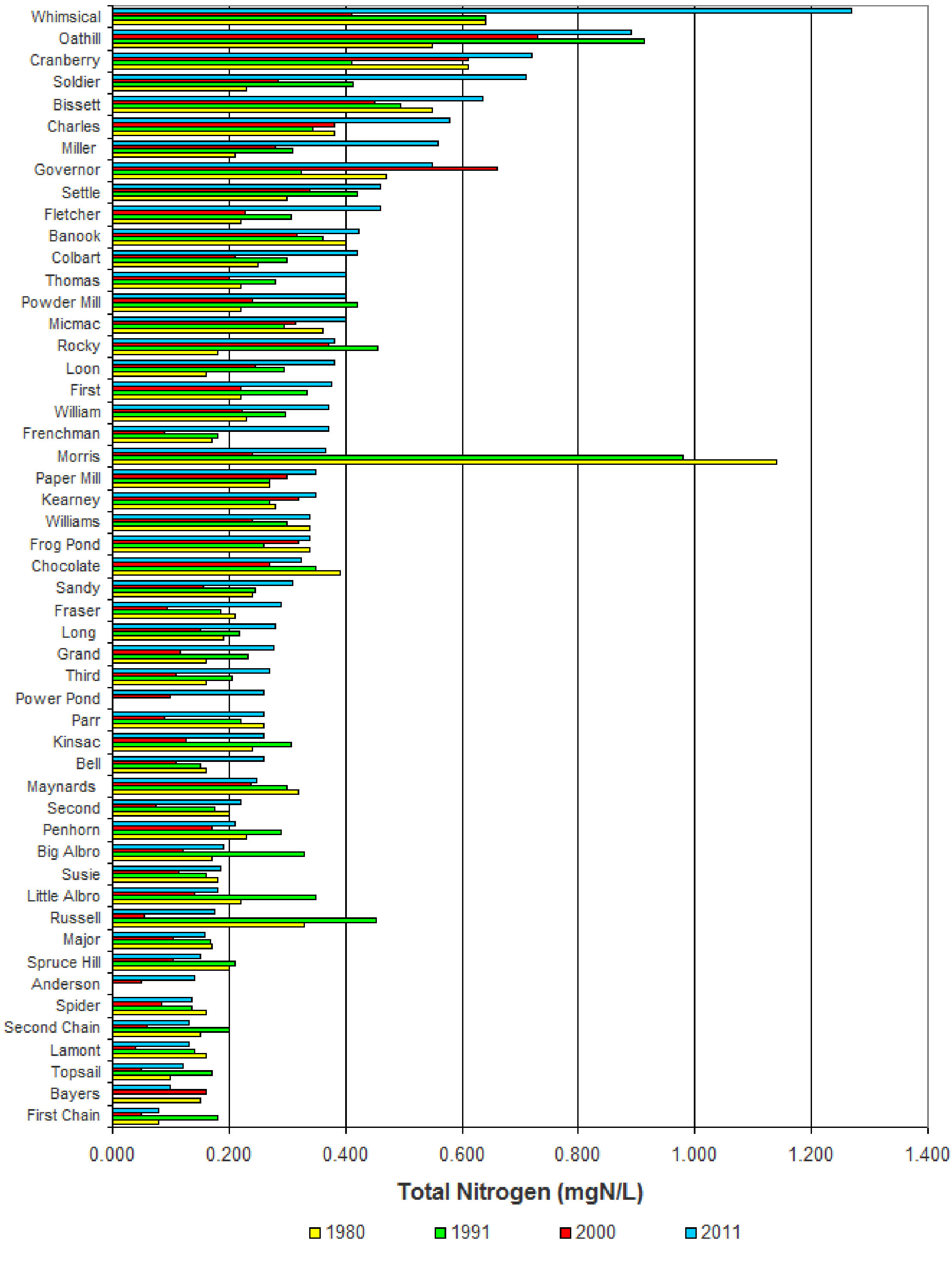

Figure 18. Total nitrogen concentrations. The CCME water quality guideline is 1.0 mg/L.

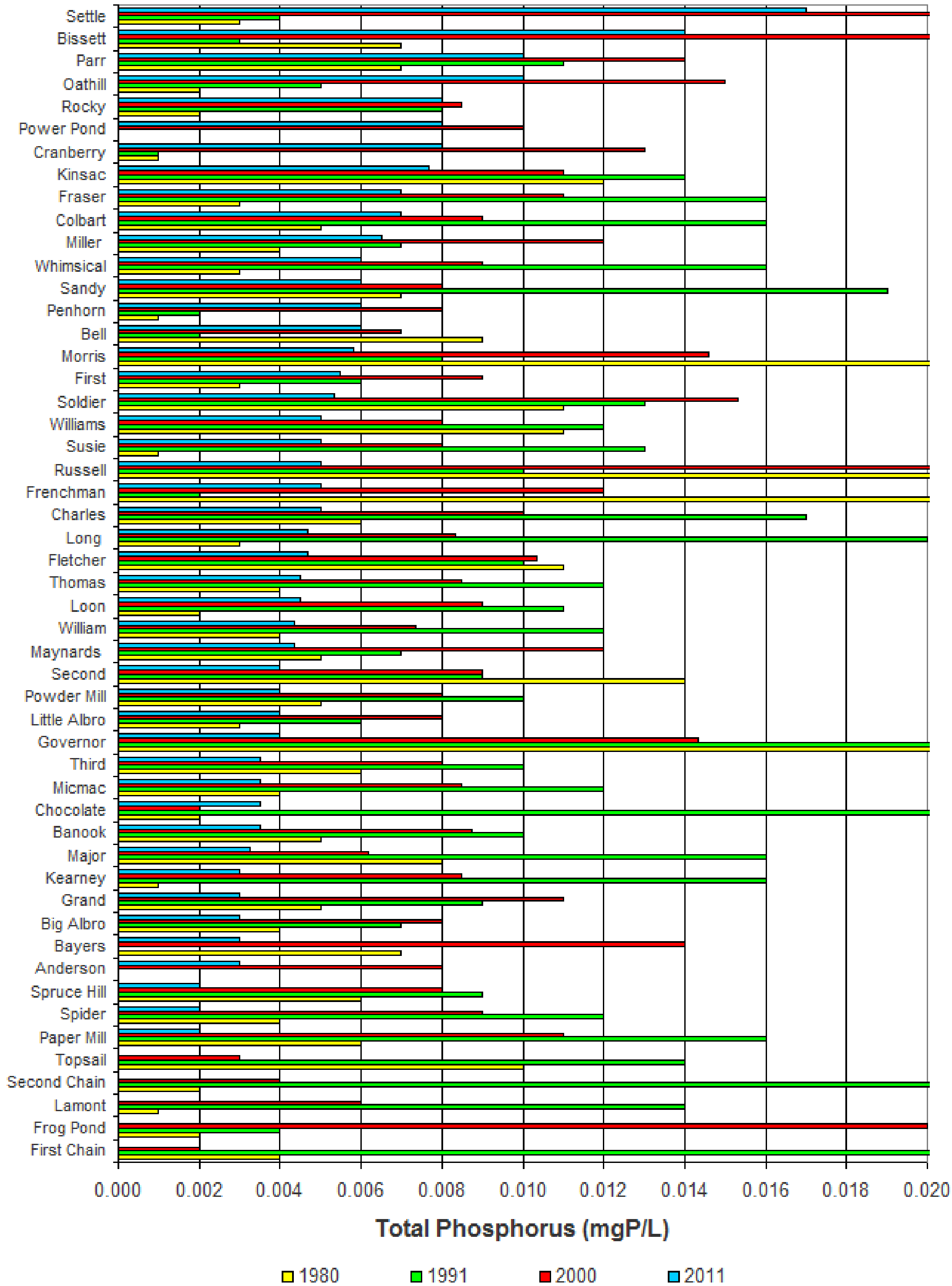

Figure 19. Total phosphorus concentrations. The CCME water quality guideline is 0.05 mg/L.

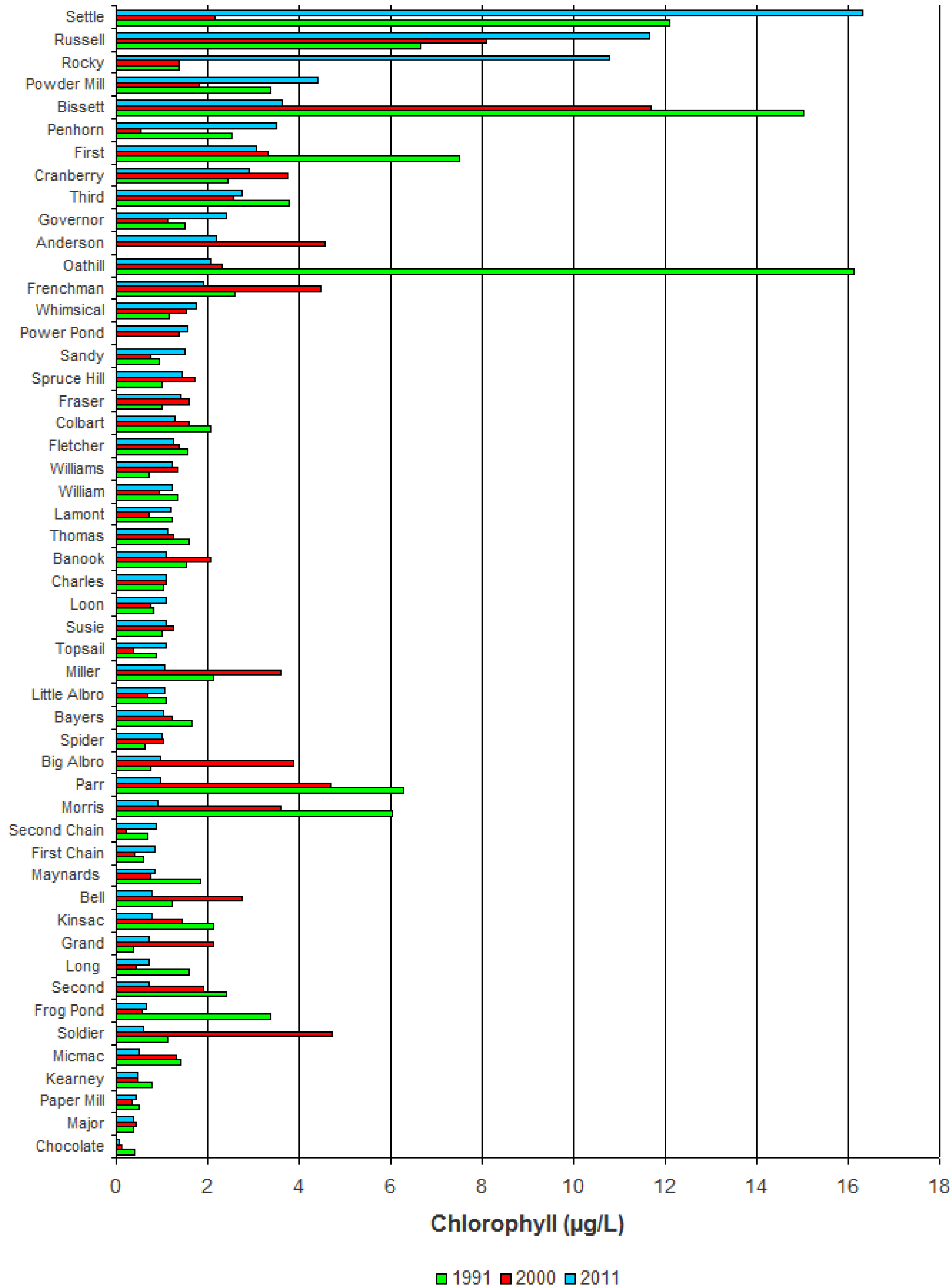

Figure 20. Chlorophyll concentrations.

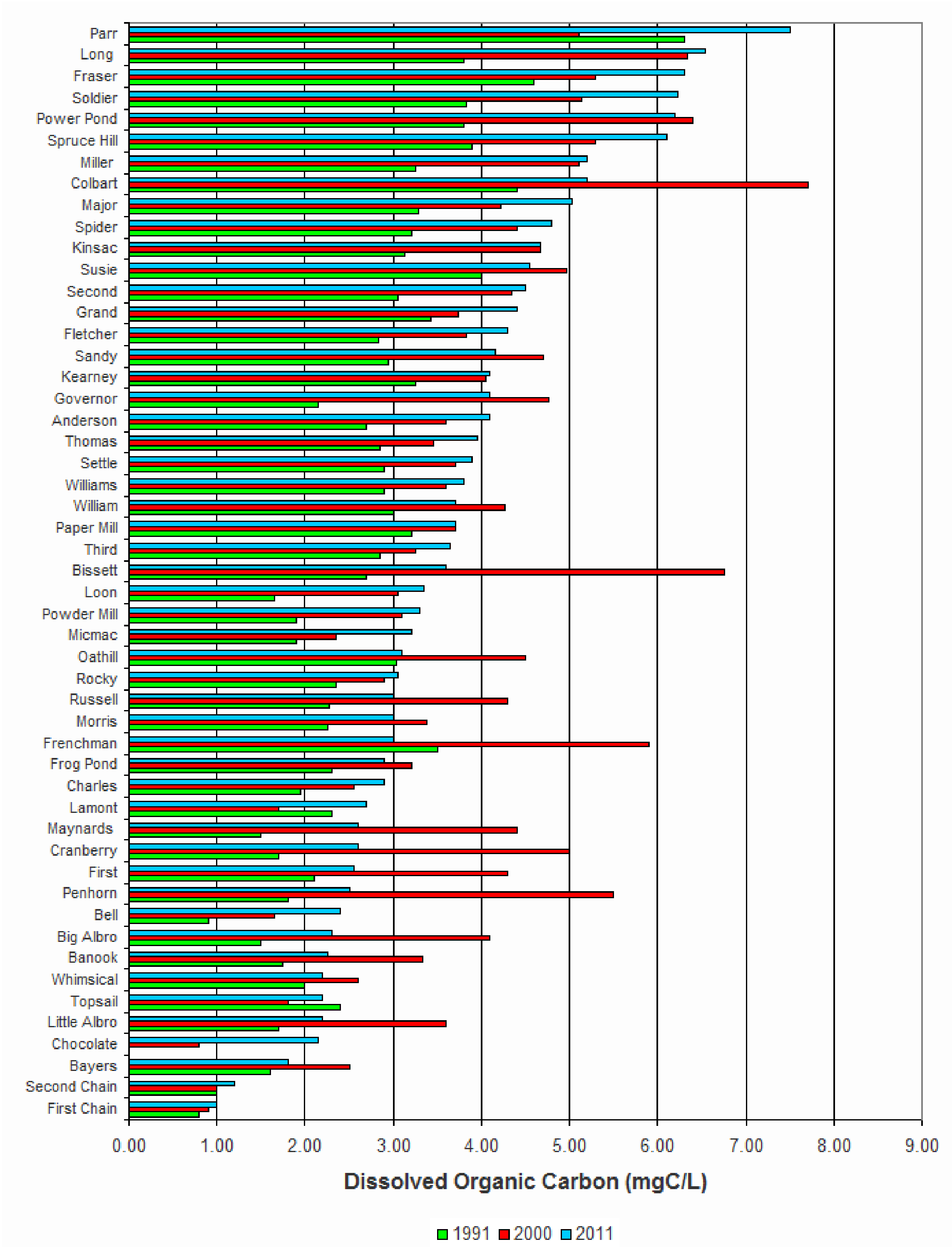

Figure 21. Dissolved organic carbon concentrations.

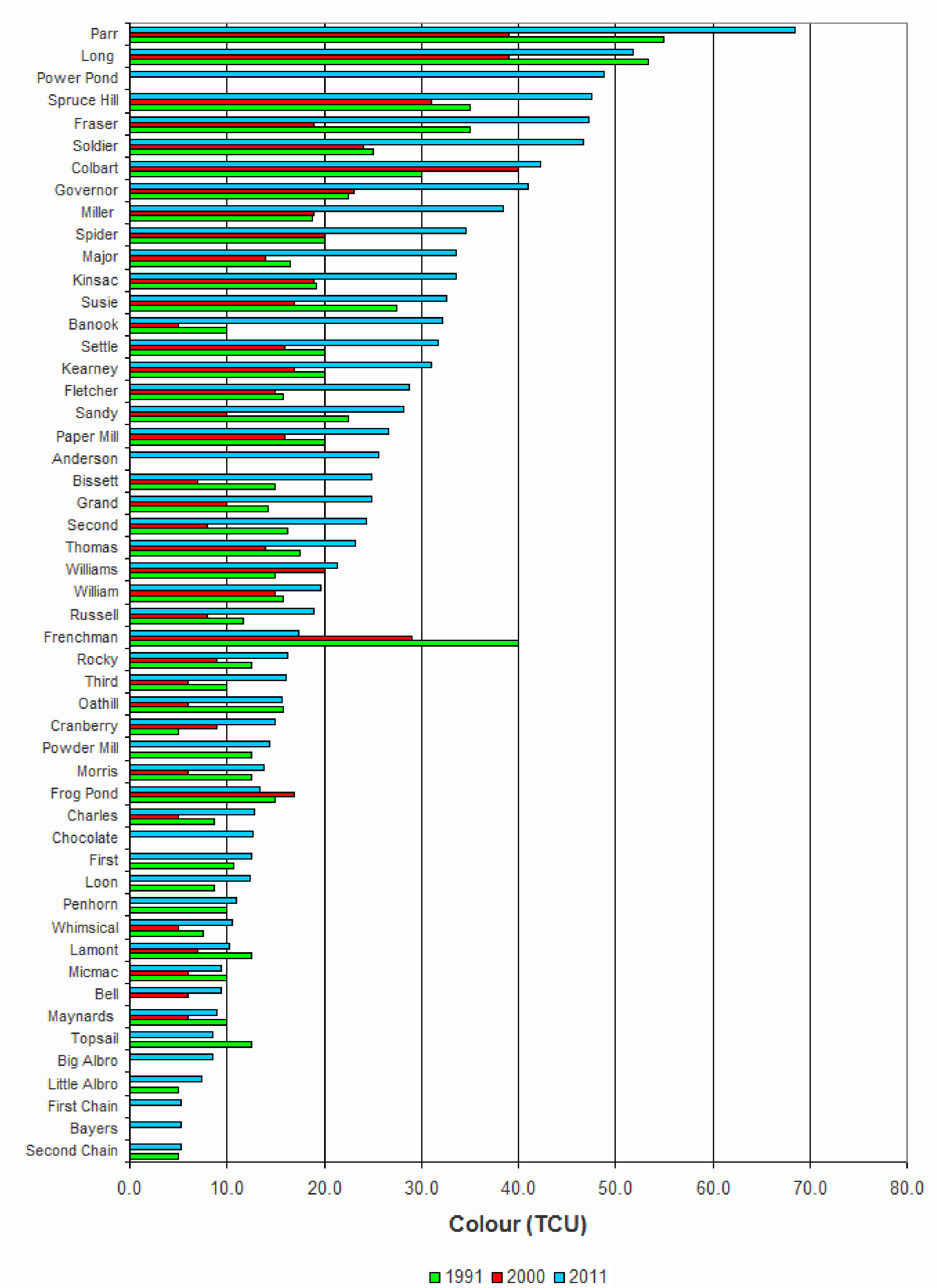

Figure 22. Colour readings.

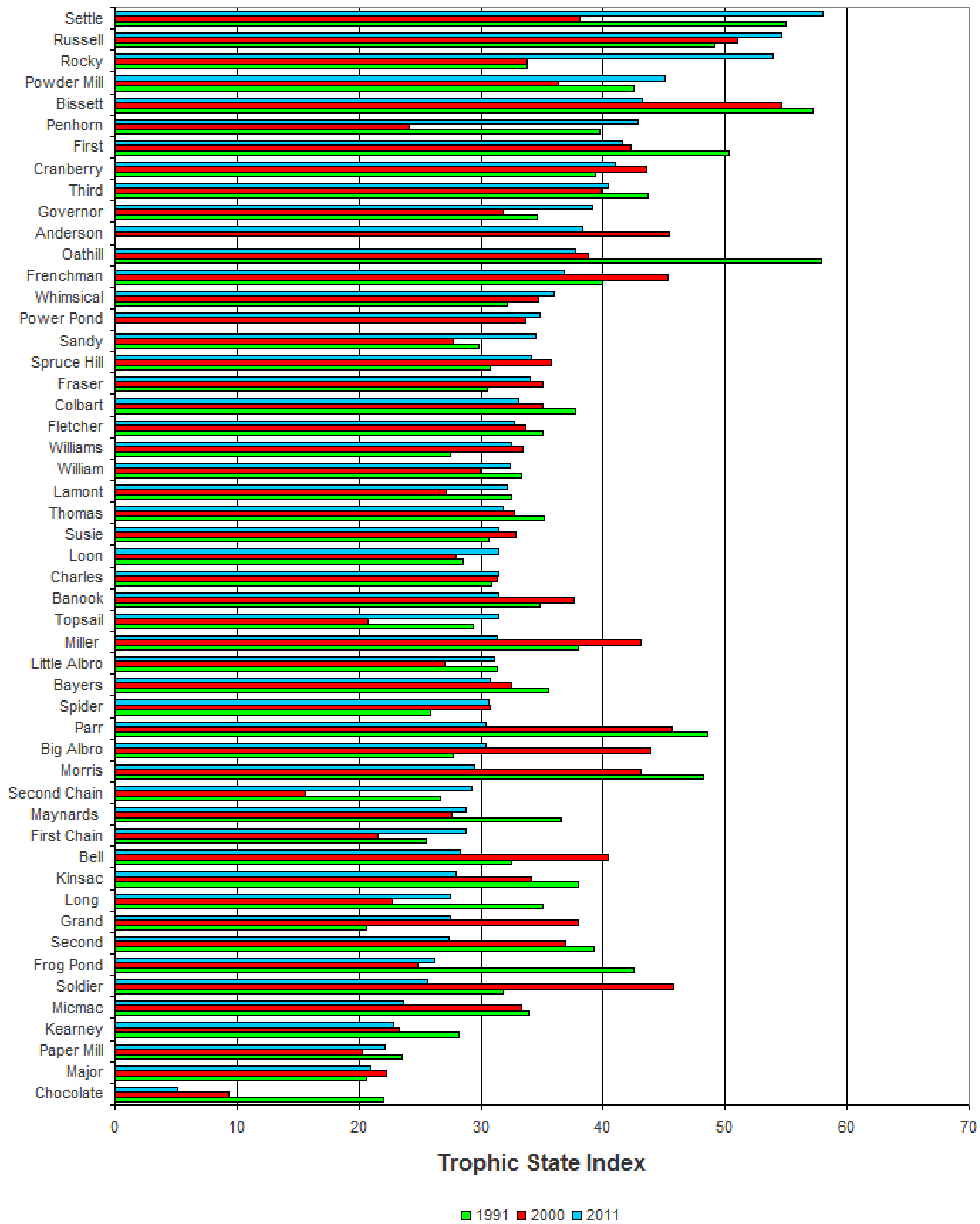

Figure 23. Trophic state index calculated using chlorophyll concentrations.

Table 4. Mean concentrations and relative standard deviations (%RSD) of all variables in all lakes for each survey. Except for 1980, 86 locations were sampled in each survey (95 locations were sampled in 1980). ND indicates not measured.

		1980		1991		2000		2011	
Variable	Units	Mean	%RSD	Mean	%RSD	Mean	%RSD	Mean	%RSD
pH	Std Units	6.03	0.91	5.93	0.85	6.27	0.64	6.23	0.85
Conductivity	µS/cm	156	130	267	213	271	181	374	295
Sodium	mg/L	20.6	18.6	37.8	32.3	39.5	28.3	57.4	59.7
Calcium	mg/L	6.2	5.7	7.3	5.3	8.3	5.3	10.1	6.9
Magnesium	mg/L	1.1	0.6	1.3	0.7	1.3	0.6	1.4	0.7
Potassium	mg/L	0.9	0.6	1.1	0.6	0.9	0.5	1.2	0.5
Aluminum	mg/L	ND		0.38	0.75	0.14	0.17	0.13	0.12
Chloride	mg/L	34.9	32.5	61.2	53.1	64.9	46.6	91.2	78.0
Sulphate	mg SO_4/L	13.9	8.4	15.3	11.7	12.2	5.5	12.1	8.1
Alkalinity	mg $CaCO_3$/L	4.6	5.6	5.3	6.2	7.0	8.4	9.2	9.0
Ammonia	mg N/L	0.037	0.048	0.012	0.015	0.019	0.019	0.034	0.12
Nitrate	mg N/L	0.08	0.08	0.15	0.13	0.19	0.15	0.17	0.14
Phosphate	mg P/L	0.004	0.006	0.003	0.002	0.003	0.002	0.001	0.001
Silica	mg Si/L	0.27	0.33	0.12	0.10	0.17	0.19	0.29	0.24
Total N	mg N/L	0.28	0.18	0.32	0.17	0.23	0.16	0.35	0.22
Total P	mg P/L	0.007	0.008	0.012	0.006	0.010	0.005	0.005	0.003
Chlorophyll	µg/L	ND		2.66	3.47	2.00	2.08	2.05	2.94
DOC	mg C/L	ND		2.7	1.0	4.0	1.4	3.7	1.5
Colour	TCU	ND		18.1	11.2	13.1	10.7	23.8	14.6
TSI		ND		35.4	8.9	33.4	9.1	33.1	8.7

Table 5. Pair-wise comparisons of the mean concentrations of all variables in all lakes for different surveys. Degrees of freedom is 43. Significant t-values are marked in bold.

Variable	1991 vs 1980	2000 vs 1980	2011 vs 1980	2011 vs 1991
pH	-1.9	**3.0**	**2.4**	
Conductivity	-0.8	**7.8**	**6.8**	
Sodium	**6.3**	**7.9**	**4.9**	
Calcium	-4.1	**7.9**	**6.5**	
Magnesium	**2.3**	**3.1**	**5.1**	
Potassium	**4.5**	-0.4	**5.3**	
Aluminum				**-2.03**
Chloride	**4.3**	**5.3**	**9.9**	
Sulphate	1.4	**-2.9**	**-2.3**	
Alkalinity	**2**	**4.3**	**7.0**	
Ammonia	**-3.9**	**-2.6**	**-2.6**	
Nitrate	**5.2**	**6.6**	**6.8**	
Phosphate	-0.7	-0.7	**-2.6**	
Silica	**-3.4**	**-1.8**	0.4	
Total N	-2.3	**-2.5**	**2.7**	
Total P	**2.8**	**2.2**	0.2	
Chlorophyll				**-4.1**
DOC				**6.5**
Colour				**2.8**
TSI				-1.3

TRACE ELEMENTS

Comparison of the 2011 trace element results with those of earlier surveys is complicated by the fact that the suite of elements analyzed and their detection limits changed over time. However, 29 elements, listed in Table 6 in order of decreasing mean concentration along with detection limits, were measured in the 1991, 2000 and 2011 surveys. With the exception of thulium, lutetium and indium, whose mean concentrations were below the detection limits, the results are plotted in Figures 24-49. The concentrations of trace elements observed in 1991 were sporadic and often higher than those measured in 2000 and 2011and it is assumed this was due to contamination or analytical problems. Therefore, the mean concentrations for 1991 as not included in Table 6.

The three most abundant trace elements were aluminum, iron and manganese (Table 6). Aluminum (Figure 23) was also measured by the ESL (Figure 10) and there was excellent agreement between the two datasets (r^2=0.950). The highest concentrations were generally found in the lakes with the lowest pH (Figure 4), many of which overlie Halifax Group slates which are a well-known source of trace elements. The next most abundant trace elements were zinc, nickel and copper (Table 6). The remaining trace elements were found in concentrations less than 1 mg/L (Table 6).

The highest concentrations of arsenic were found in Lakes Charles (Figure 30) and are undoubtedly related to the disposal of gold mine tailings from the Montague gold mines into Mitchell Brook between the mid-1860s and the early 1940s. Runoff from these historical mine tailings continues to this day. Contamination of this stream system was documented in the 1970s (Brooks et al. 1982) and this area has been extensively studied over the last 15 years. Arsenic levels in stream water in recent years have typically ranged between 50 and 100 µg/L (M. Parsons, personal communication). Turbid waters in Lake Charles were reported during mining operations in 1938 and fine tailings have been reported in bottom sediments (Mudroch and Clair 1985). The natural drainage from Lake Charles is north into the Shubenacadie watershed (Figure 2) and relatively high values of arsenic were also observed in Lakes Williams, Thomas and Fletcher (Figure 30). Some of this arsenic may also have come from gold mine tailings in the Waverley area. Since the construction of the Shubenacadie Canal in the 1800s, water from Lake Charles also drains south into Lakes Micmac and Banook which also show relatively high values of arsenic (Figure 30).

It is interesting to note that the highest concentrations of trace elements frequently occurred in Governor, Bayers, First Chain, Second Chain and Chocolate lakes. These five lakes are located in close proximity to each other and these high concentrations are presumably related to the nearby Halifax Group slates (White et al. 2014) which are a well-known source of trace elements (White and Goodwin 2011). With the exception of cadmium, the mean concentrations of trace elements for all lakes were very similar in 2000 and 2011 (Table 6). For some unknown reason, cadmium concentrations were much lower in 2011. Uranium (Figure 39) is likely sourced from underlying granites and mobilized by the relatively low values of pH.

Table 6. The mean concentrations and detection limits of trace elements observed in all lakes in 2000 and 2011.

	2000		2011	
Element	Mean Concentration (μg/L)	Detection Limit (μg/L)	Mean Concentration (μg/L)	Detection Limit (μg/L)
Aluminum	138.7	2	114.4	2
Iron	76.61	5	78.83	5
Manganese	66.06	0.1	78.07	0.1
Zinc	8.04	0.5	8.52	0.5
Nickel	1.42	0.2	1.60	0.2
Copper	1.40	0.1	1.00	0.1
Arsenic	0.607	0.1	0.711	0.1
Vanadium	0.606	0.1	0.352	0.1
Cobalt	0.480	0.05	0.450	0.05
Lead	0.384	0.01	0.251	0.01
Cerium	0.217	0.01	0.205	0.01
Lanthanum	0.161	0.01	0.162	0.01
Cadmium	0.146	0.01	0.064	0.02
Yttrium	0.135	0.01	0.146	0.01
Neodymium	0.131	0.005	0.127	0.005
Uranium	0.047	0.005	0.051	0.005
Praseodymium	0.033	0.005	0.032	0.005
Gadolinium	0.027	0.005	0.026	0.005
Samarium	0.026	0.005	0.025	0.005
Dysprosium	0.022	0.005	0.021	0.005
Erbium	0.014	0.005	0.014	0.005
Ytterbium	0.012	0.01	0.012	0.01
Thallium	0.009	0.005	0.009	0.005
Europium	0.008	0.005	0.009	0.005
Holmium	0.006	0.005	0.006	0.005
Terbium	0.006	0.005	0.006	0.005
Thulium	0.000	0.005	0.004	0.005
Lutetium	0.001	0.005	0.003	0.005
Indium	0.000	0.005	0.000	0.01

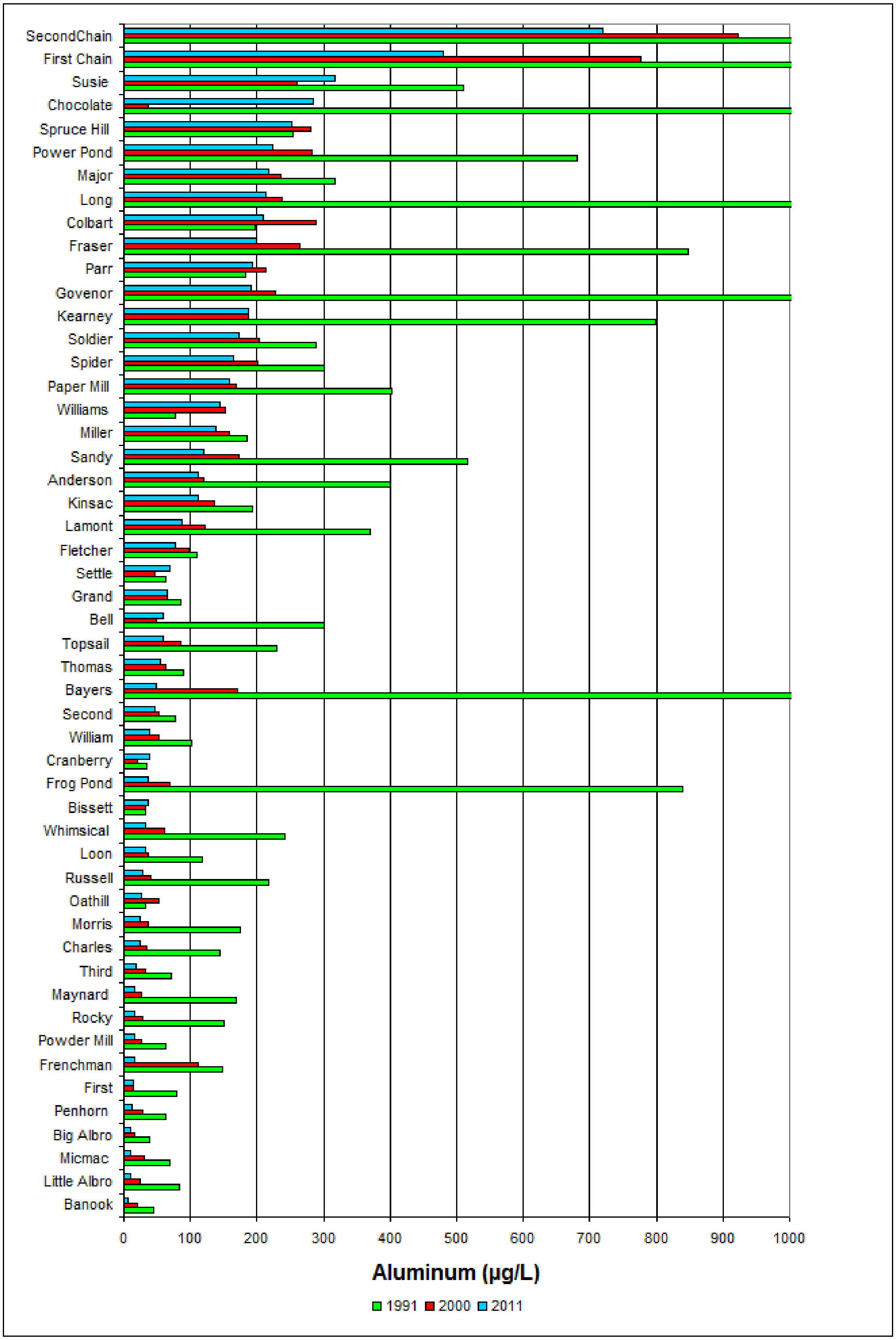

Figure 24. Aluminum concentrations measured by the Geological Survey of Canada.

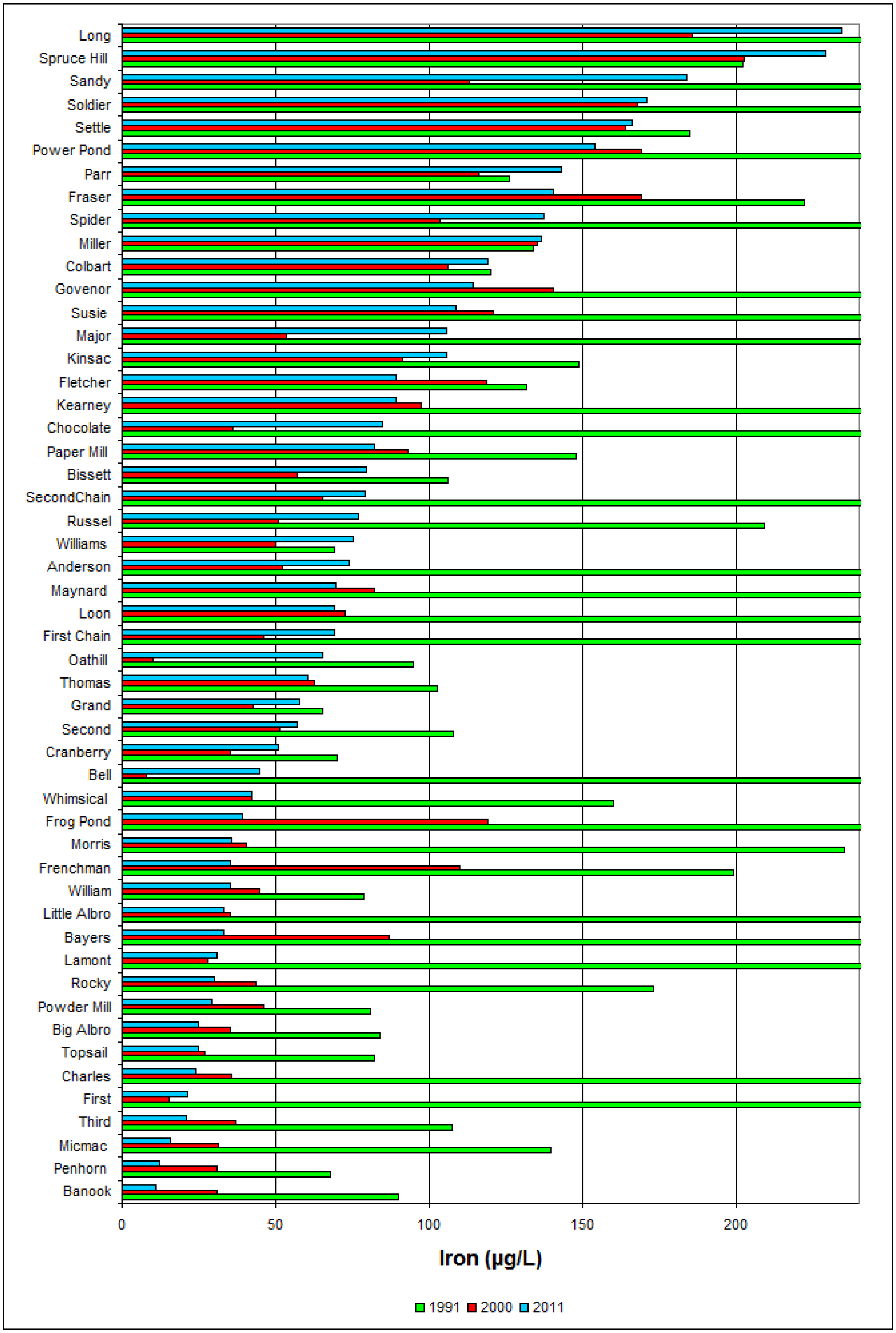

Figure 25. Iron concentrations. The CCME water quality guideline is 300 µg/L.

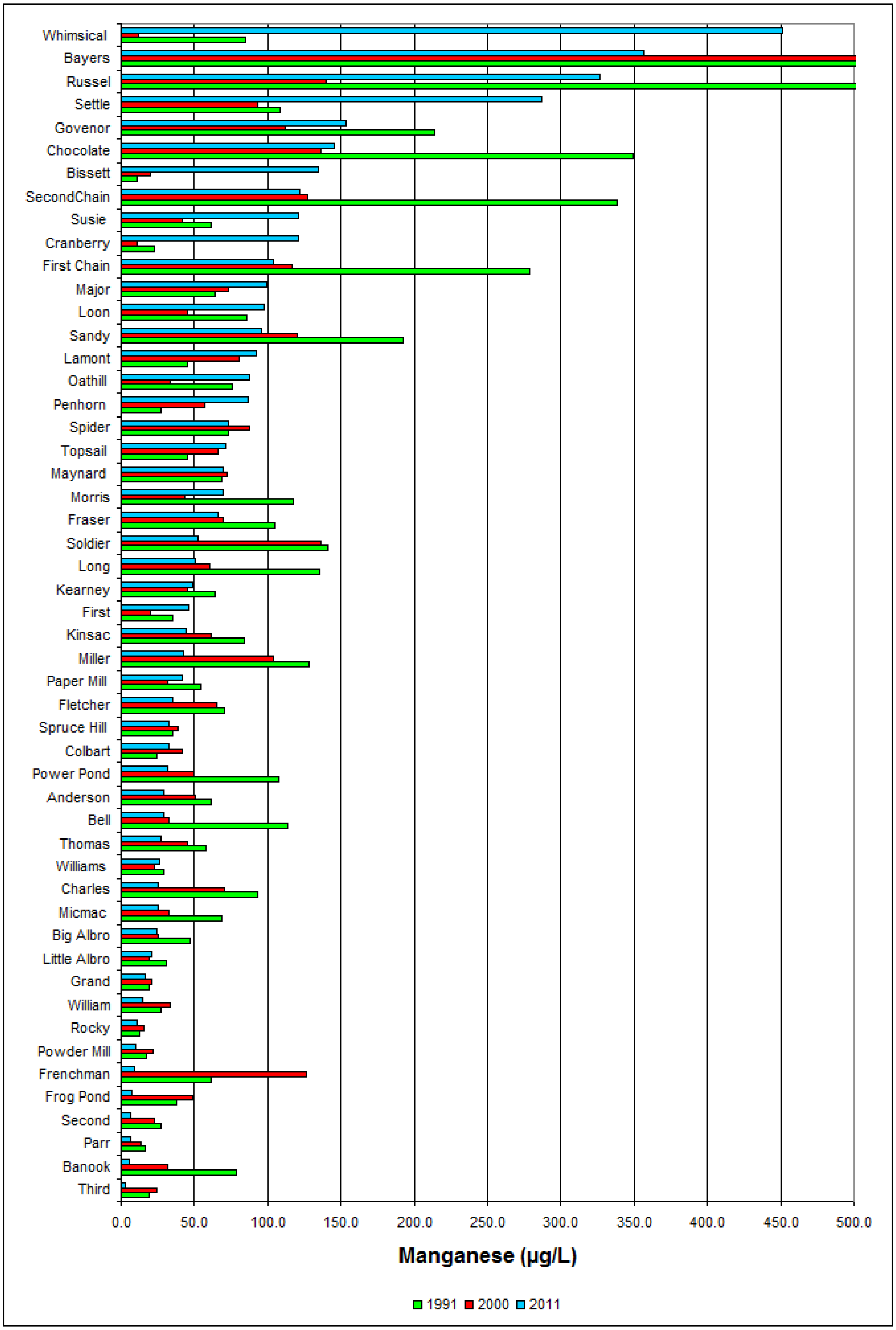

Figure 26. Manganese concentrations.

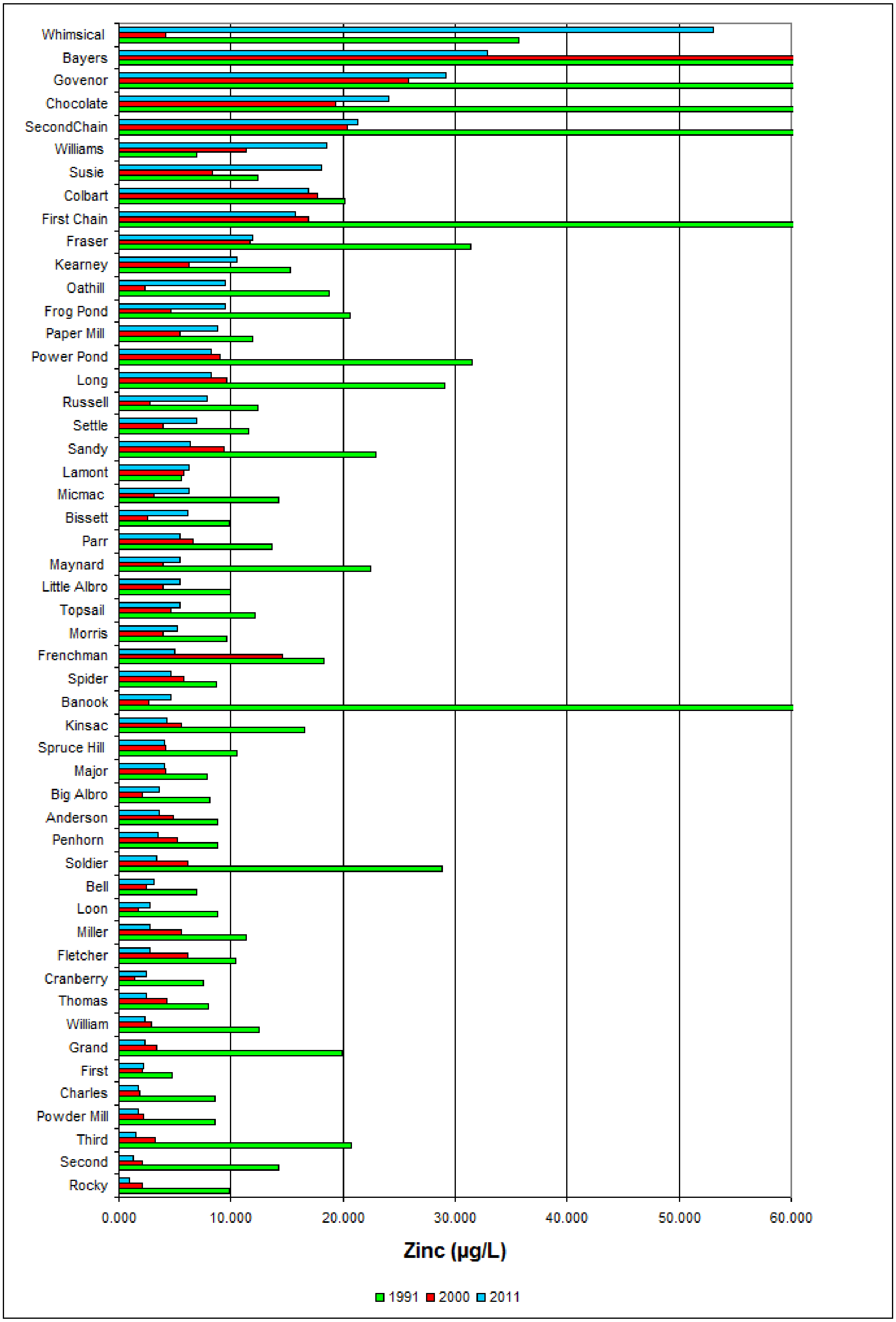

Figure 27. Zinc concentrations. The CCME water quality guideline is 7 µg/L.

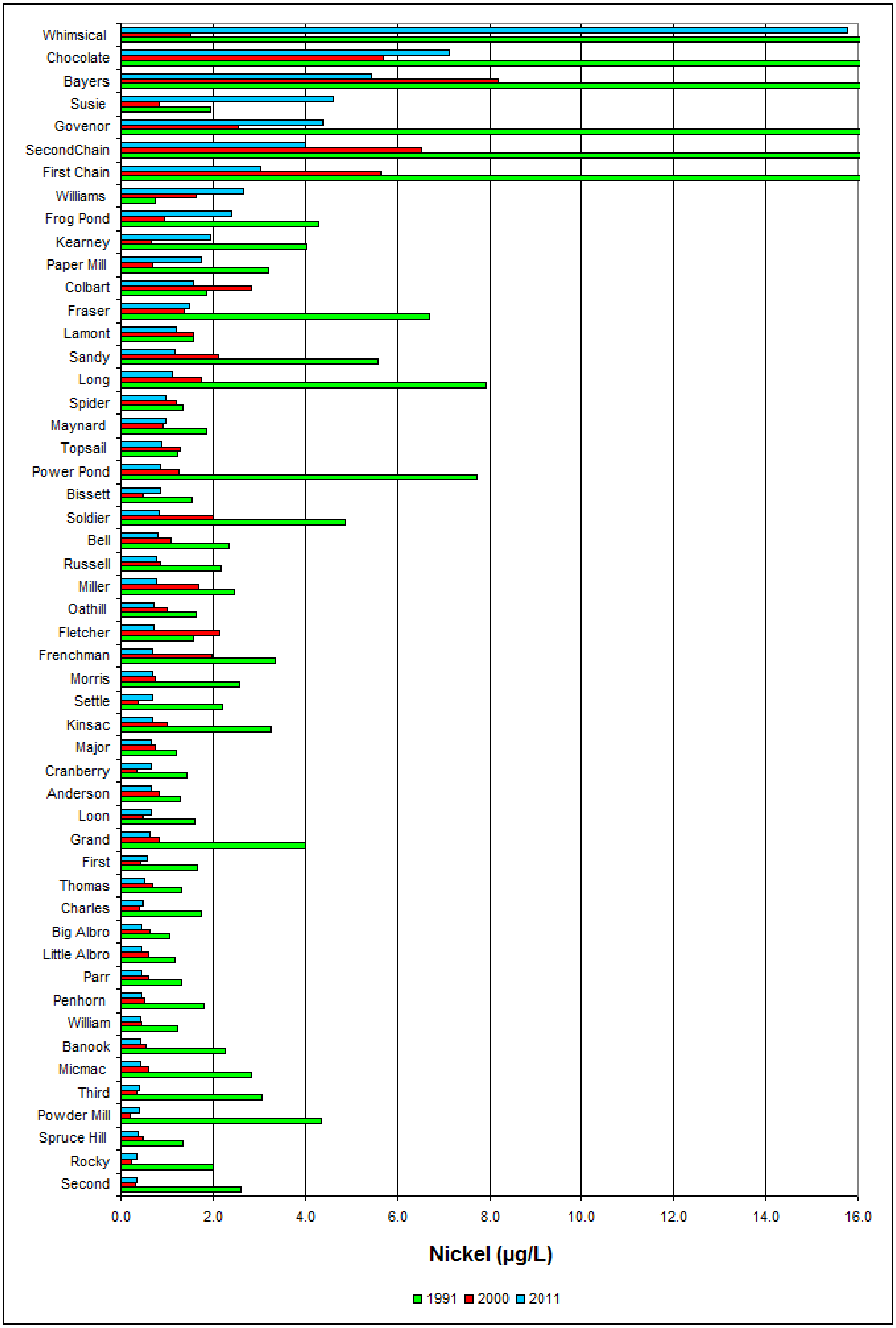

Figure 28. Nickel concentrations.

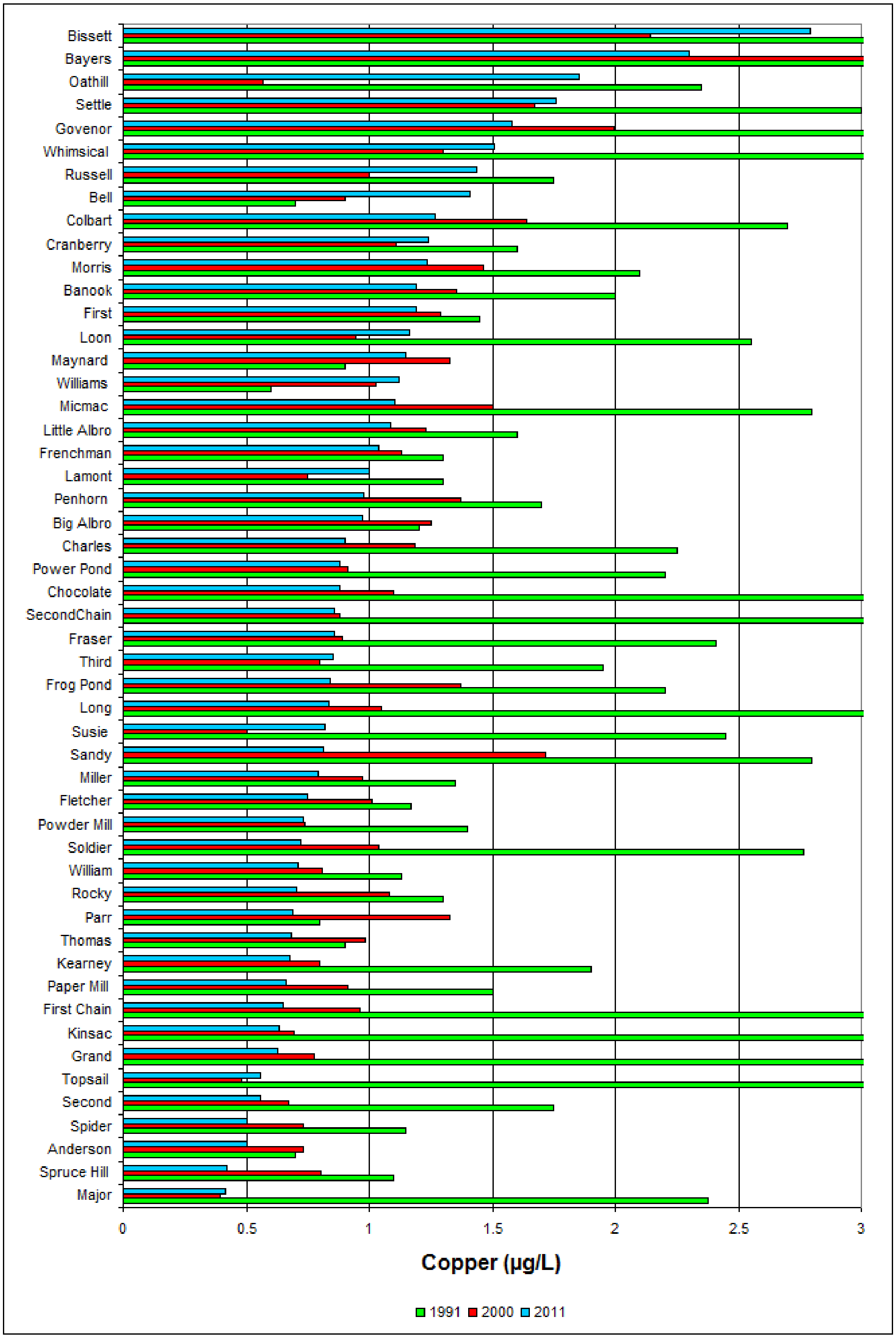

Figure 29. Copper concentrations.

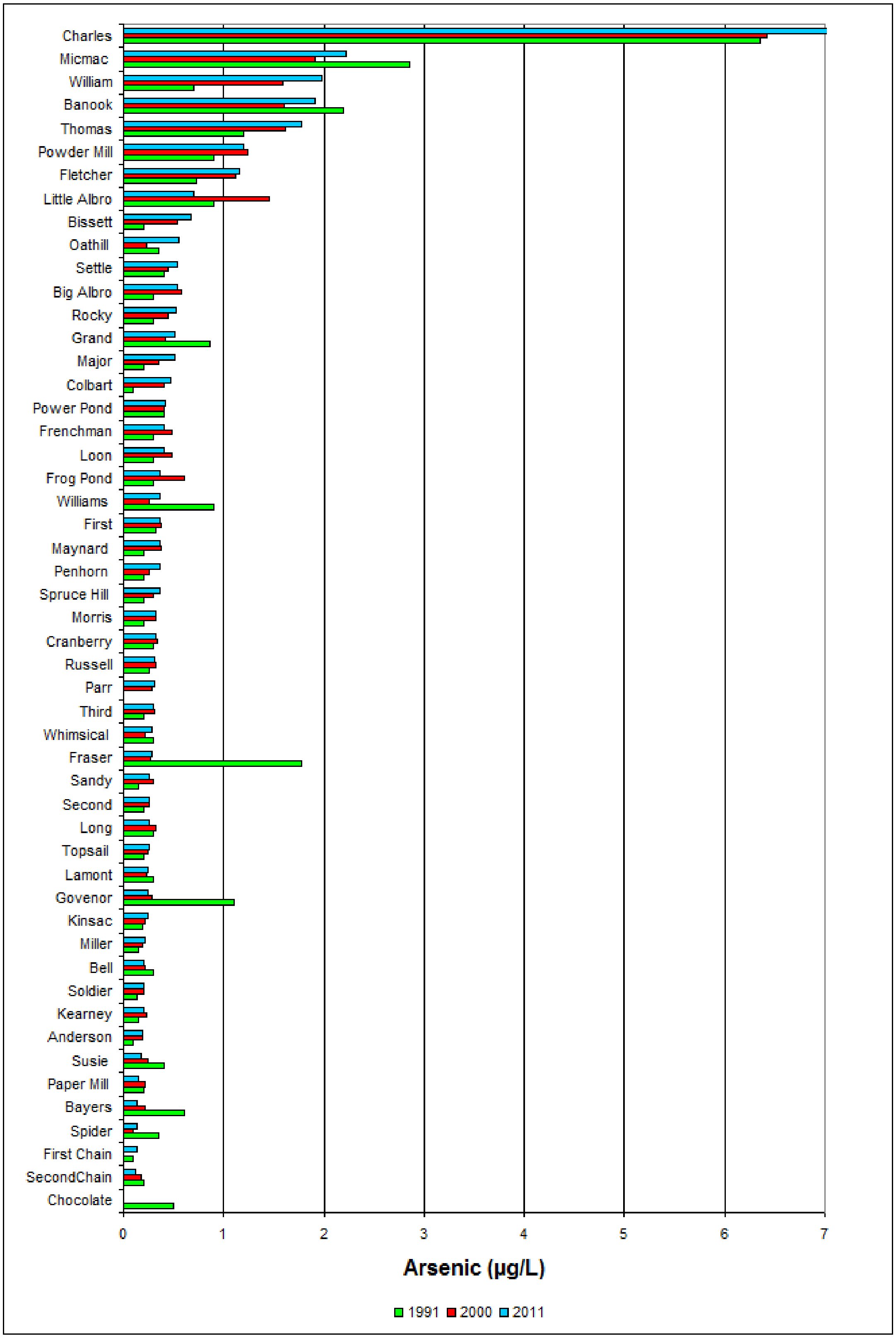

Figure 30. Arsenic concentrations. The CCME water quality guideline is 5 µg/L.

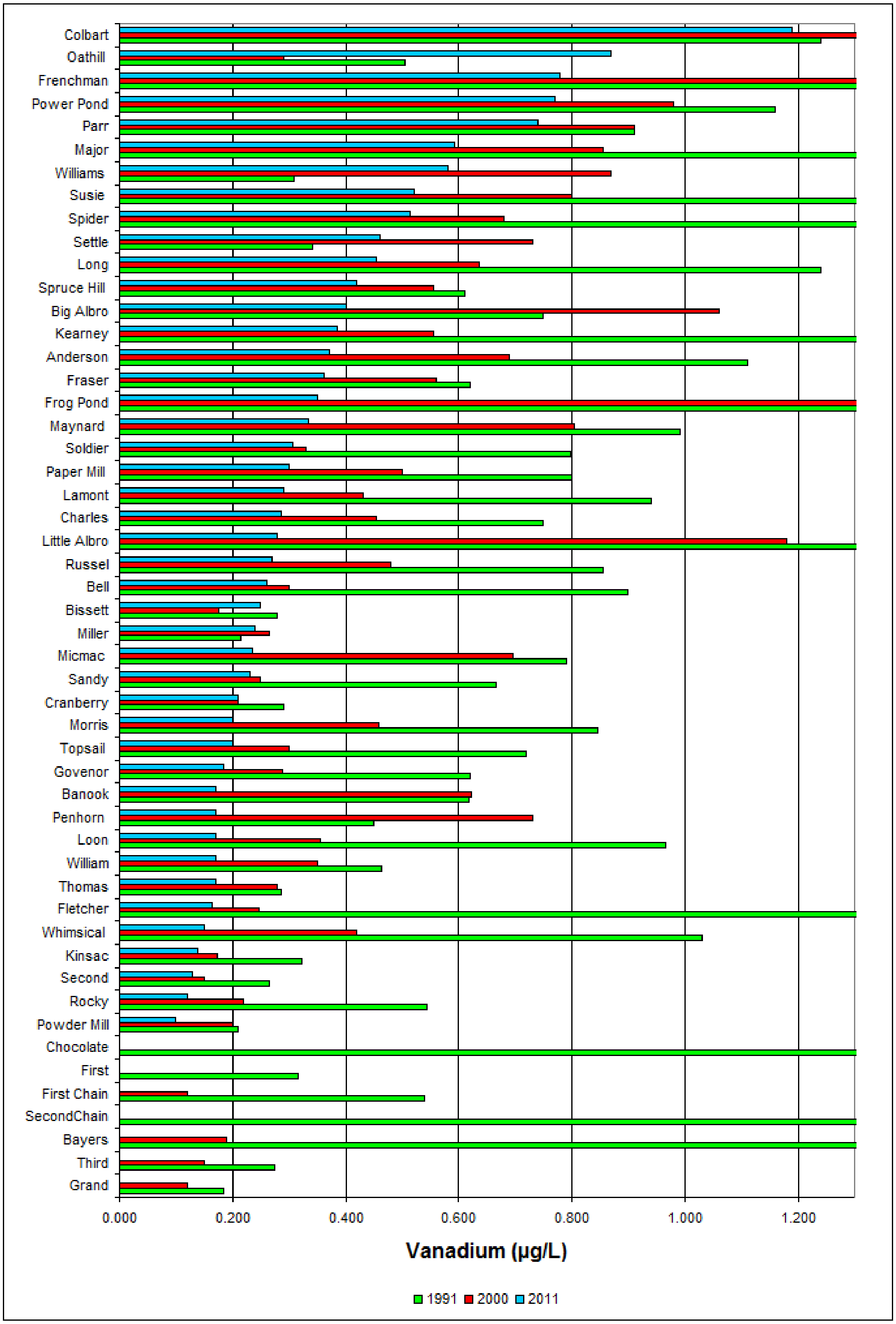

Figure 31. Vanadium concentrations.

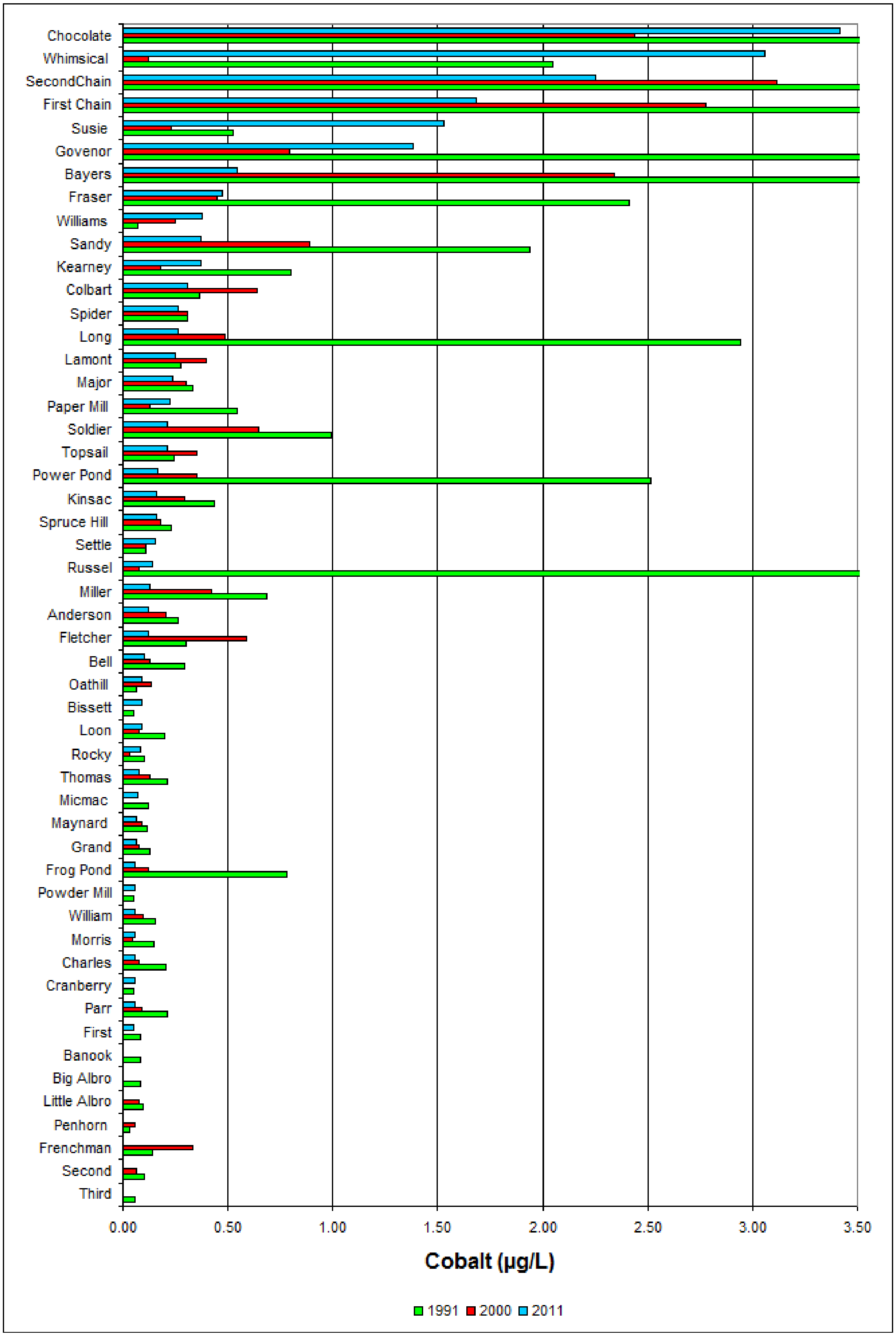

Figure 32. Cobalt concentrations.

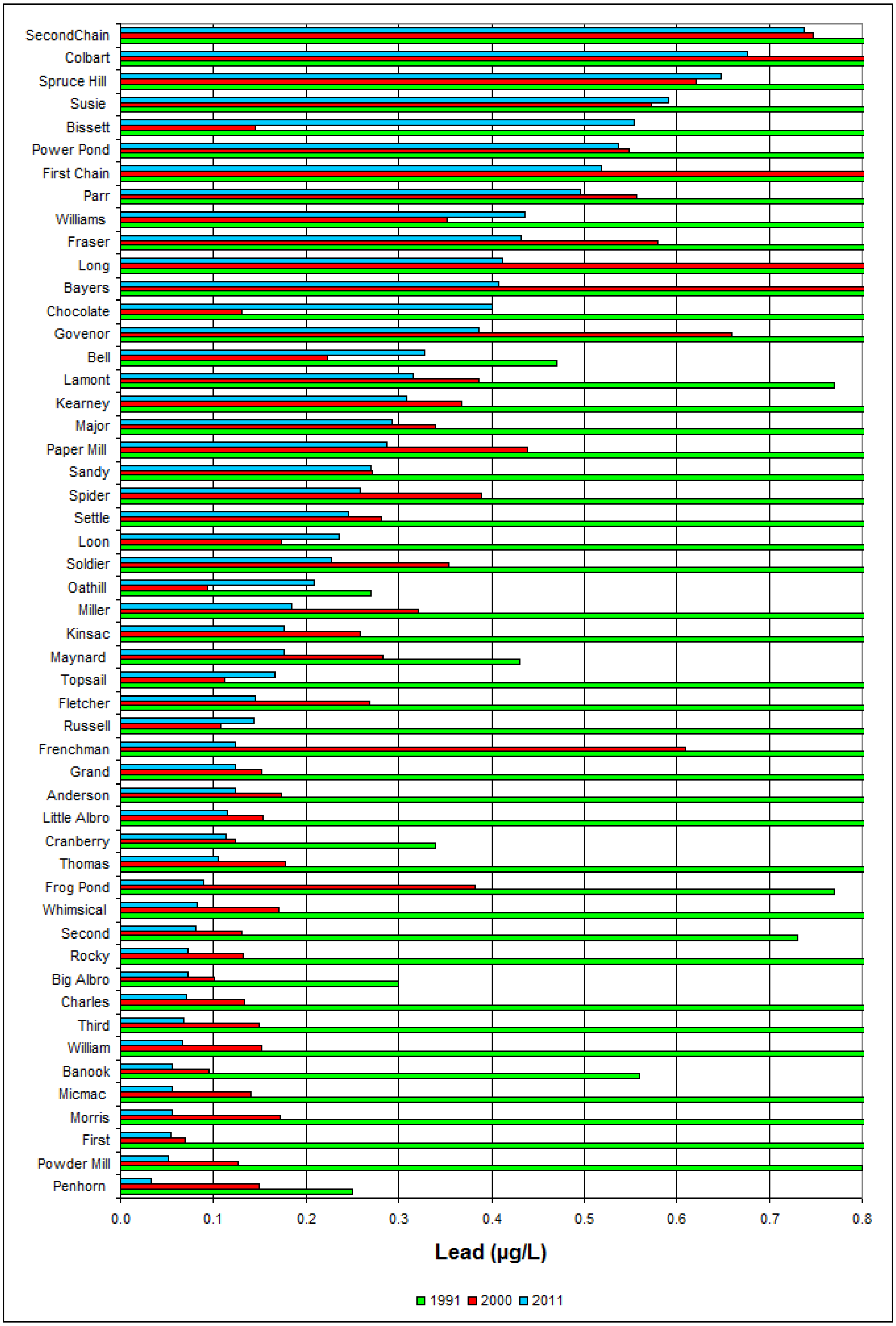

Figure 33. Lead concentrations.

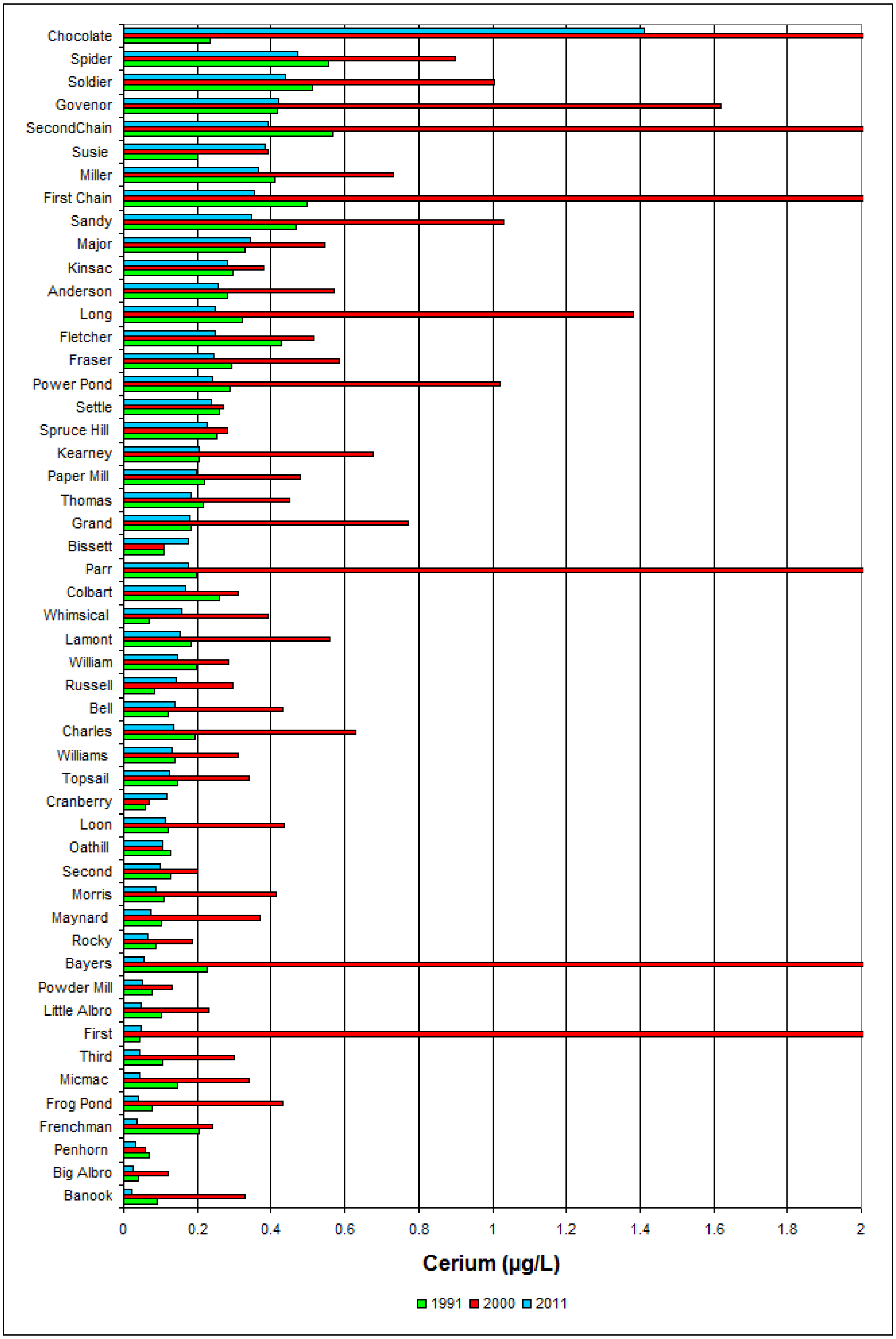

Figure 34. Cerium concentrations.

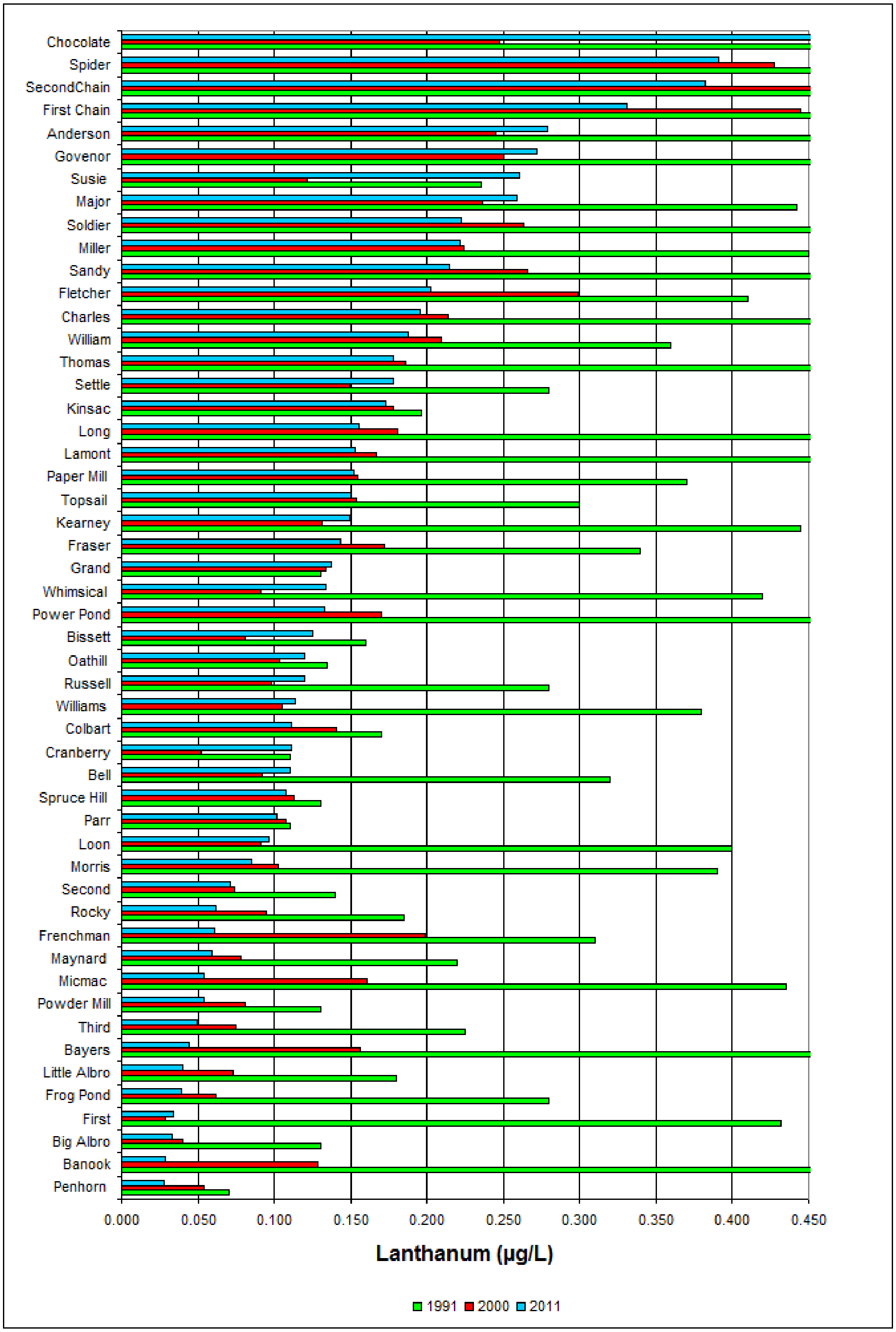

Figure 35. Lanthanam concentrations.

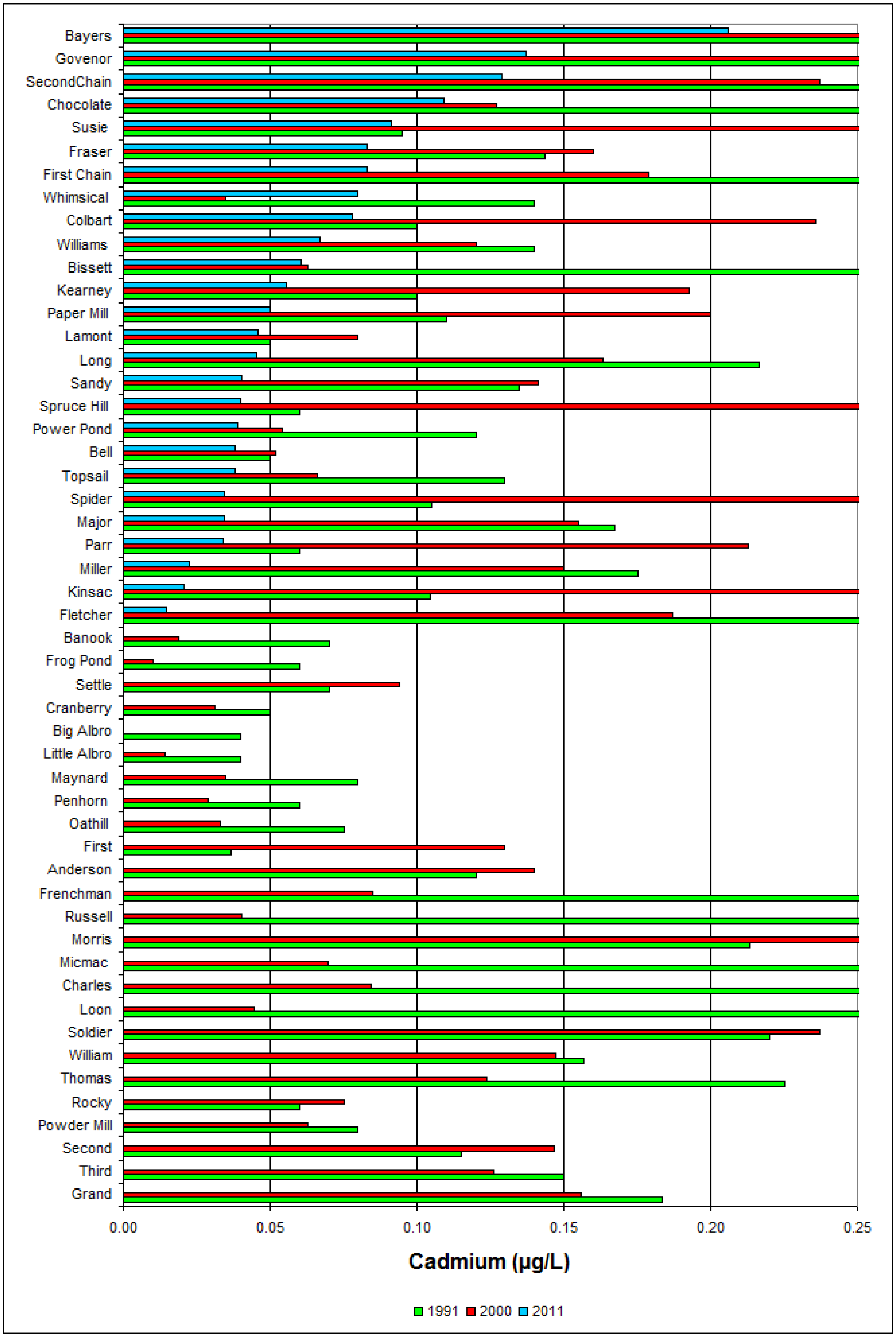

Figure 36. Cadmium concentrations. The CCME water quality guideline is 0.09 µg/L.

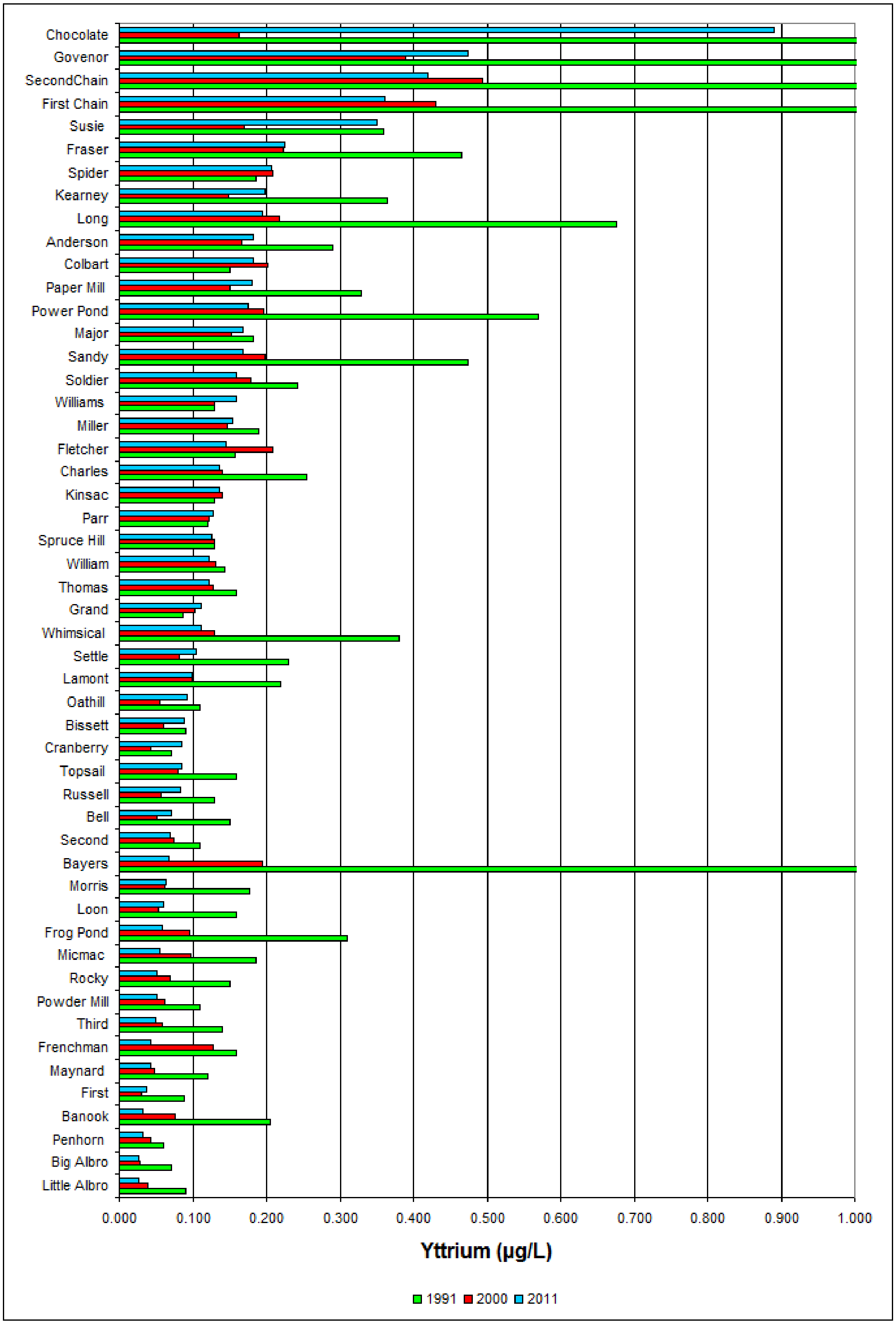

Figure 37. Yttrium concentrations.

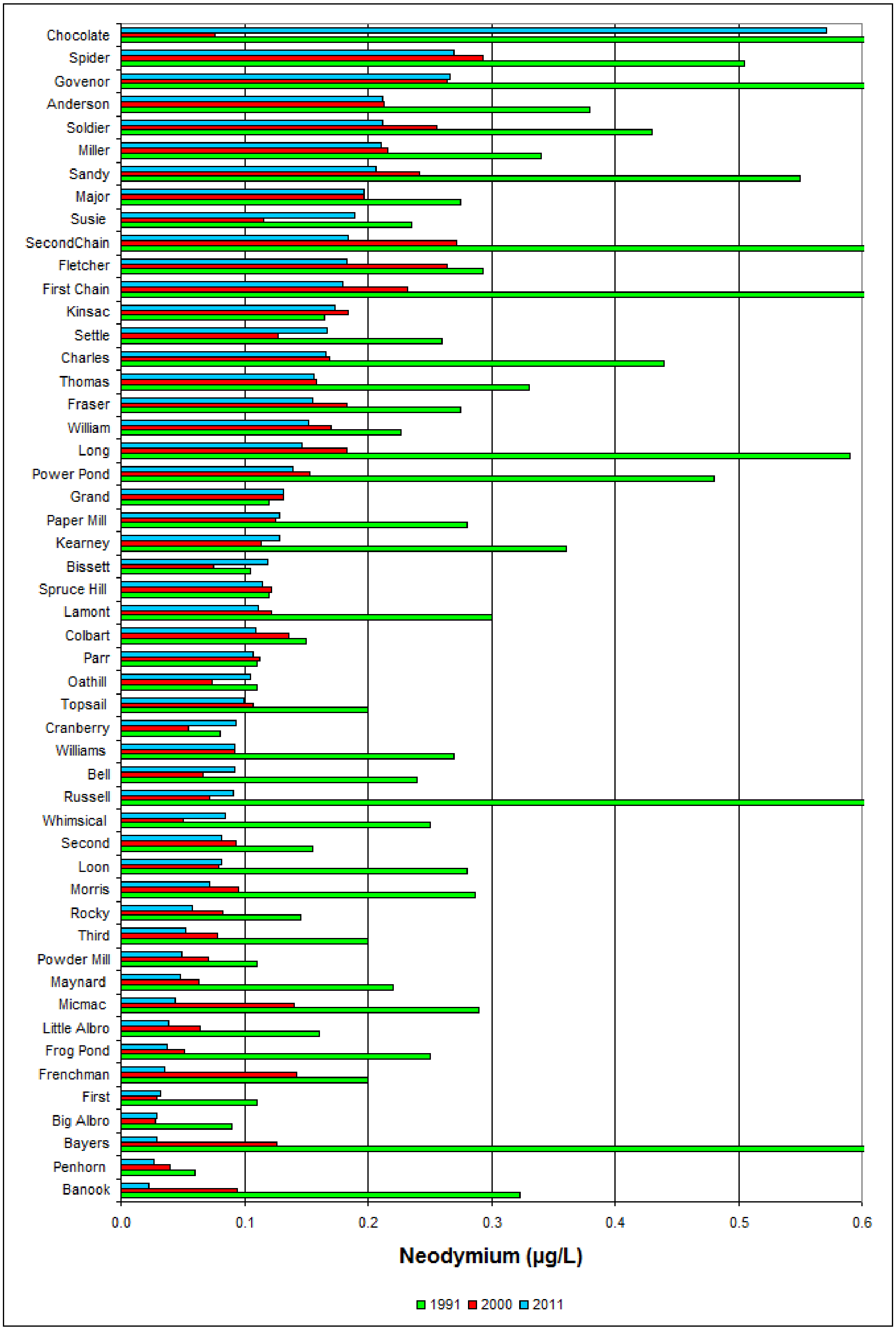

Figure 38. Neodymium concentrations.

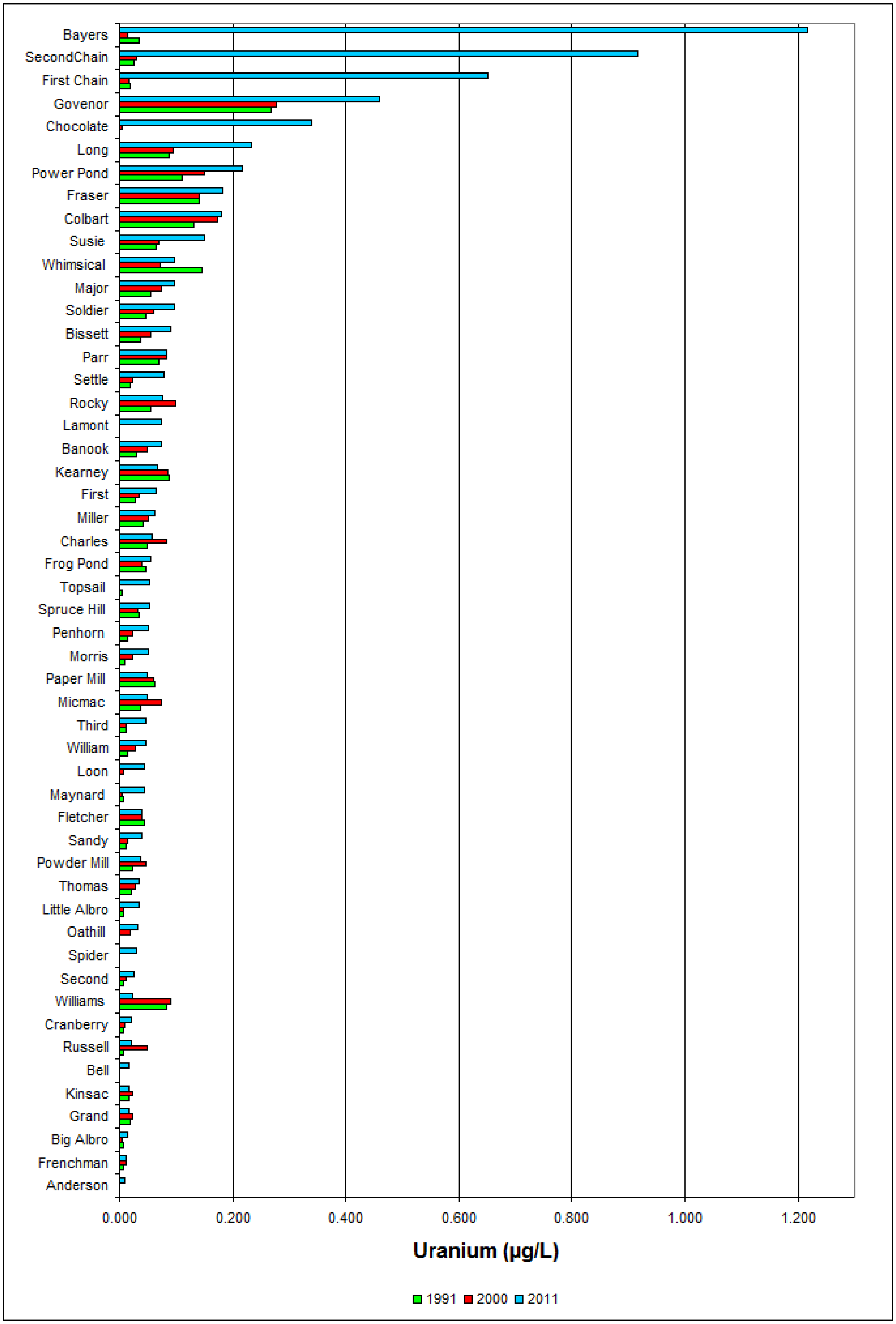

Figure 39. Uranium concentrations. The CCME water quality guideline is 15 µg/L.

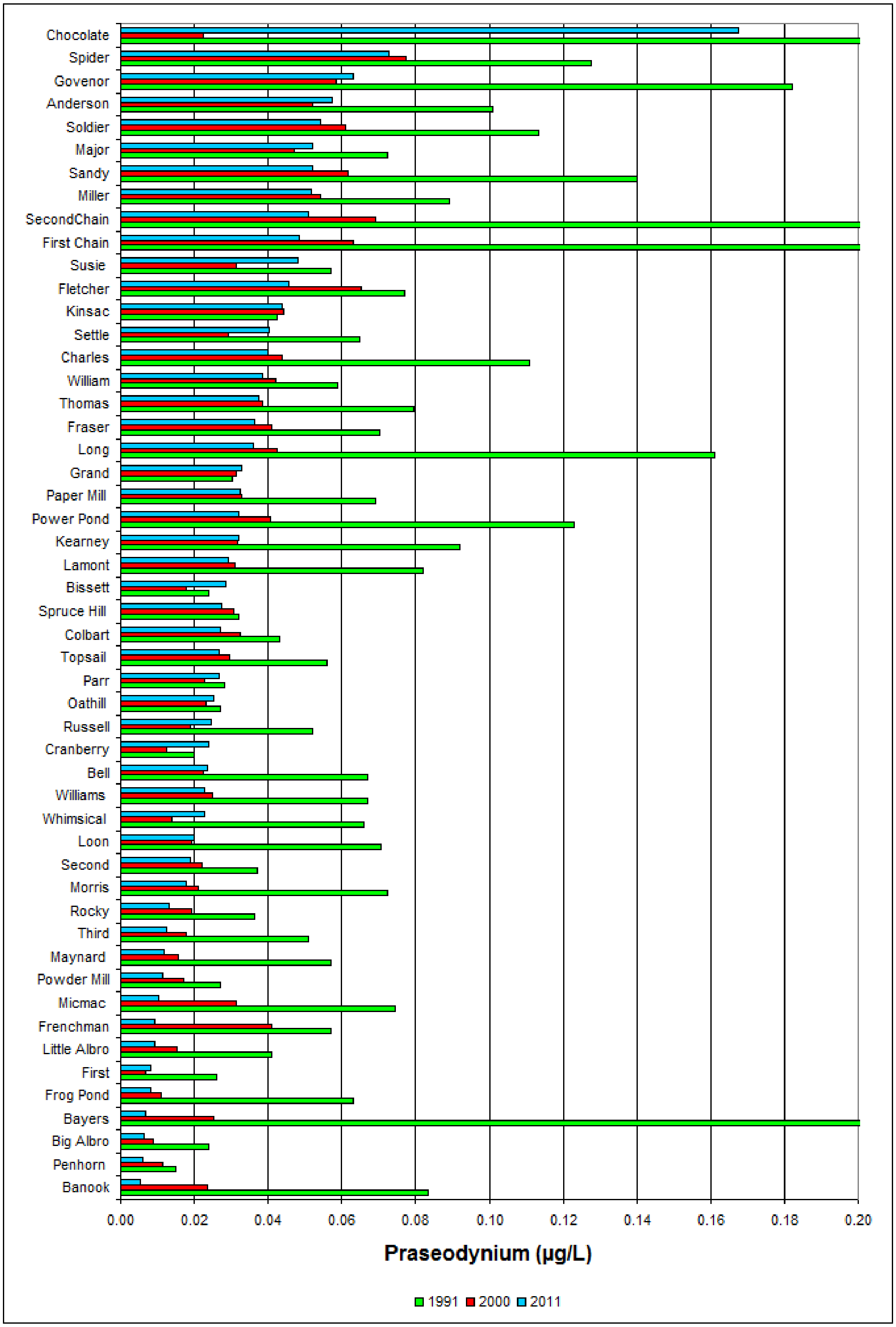

Figure 40. Praseodymium concentrations.

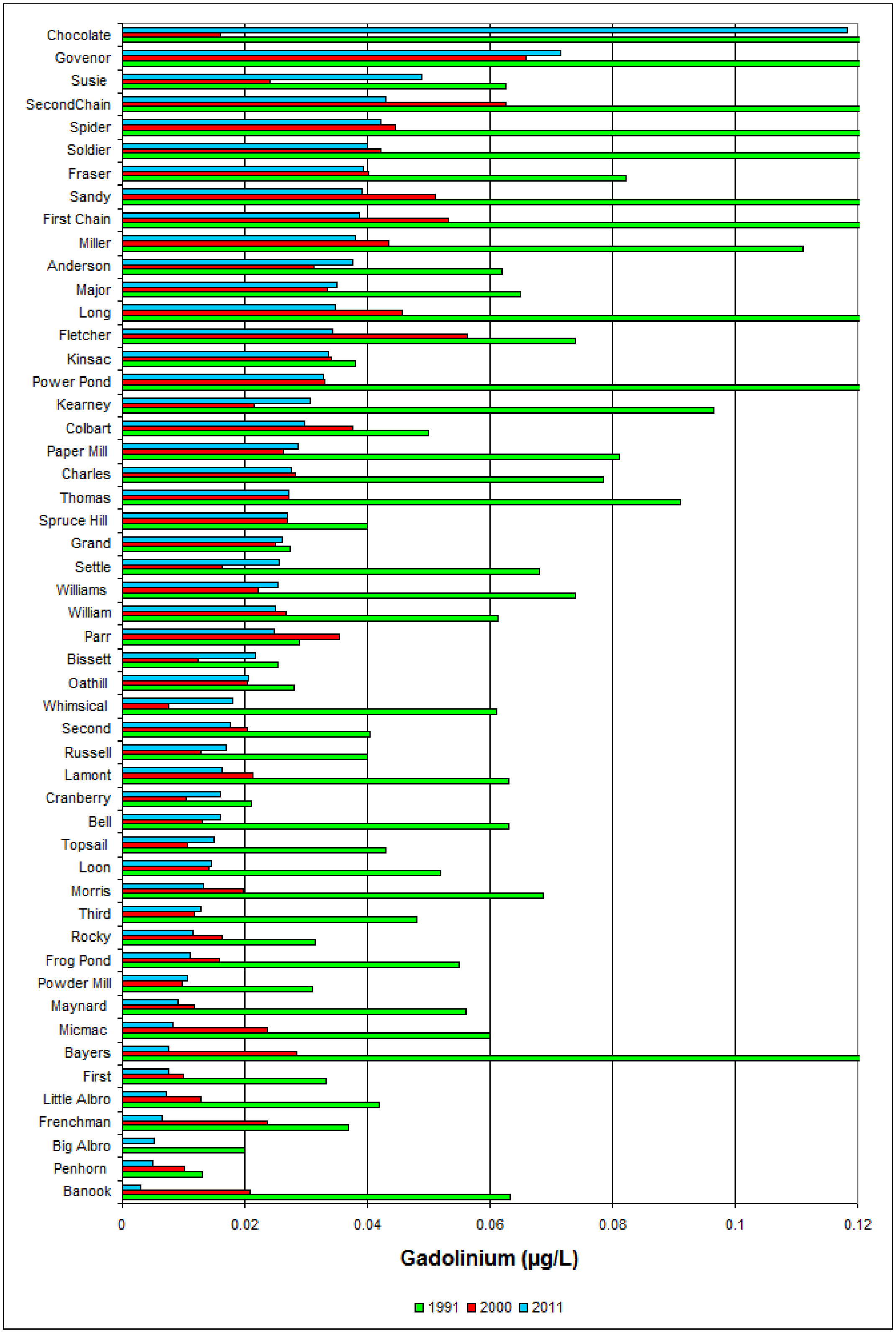

Figure 41. Gadolinium concentrations.

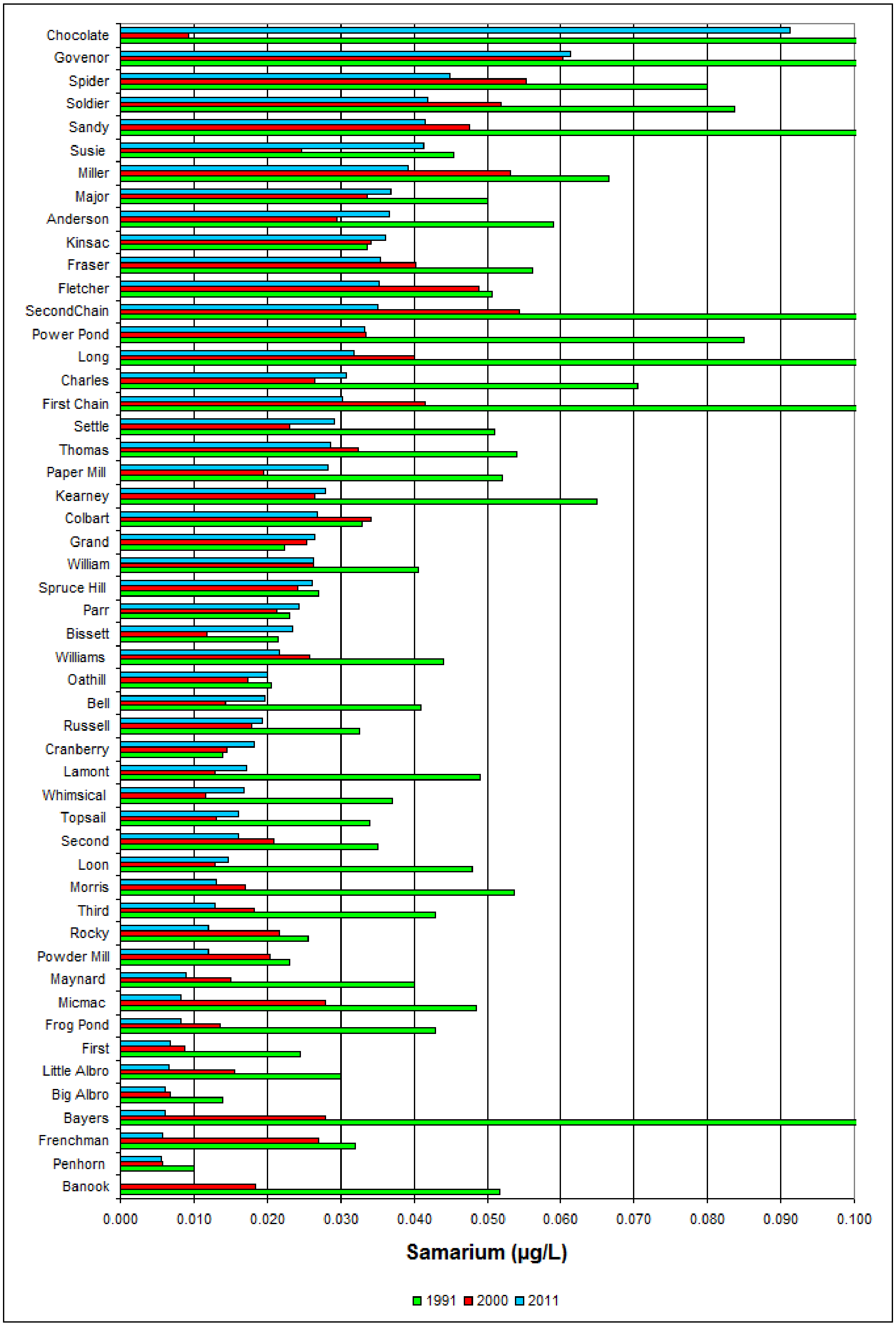

Figure 42. Samarium concentrations.

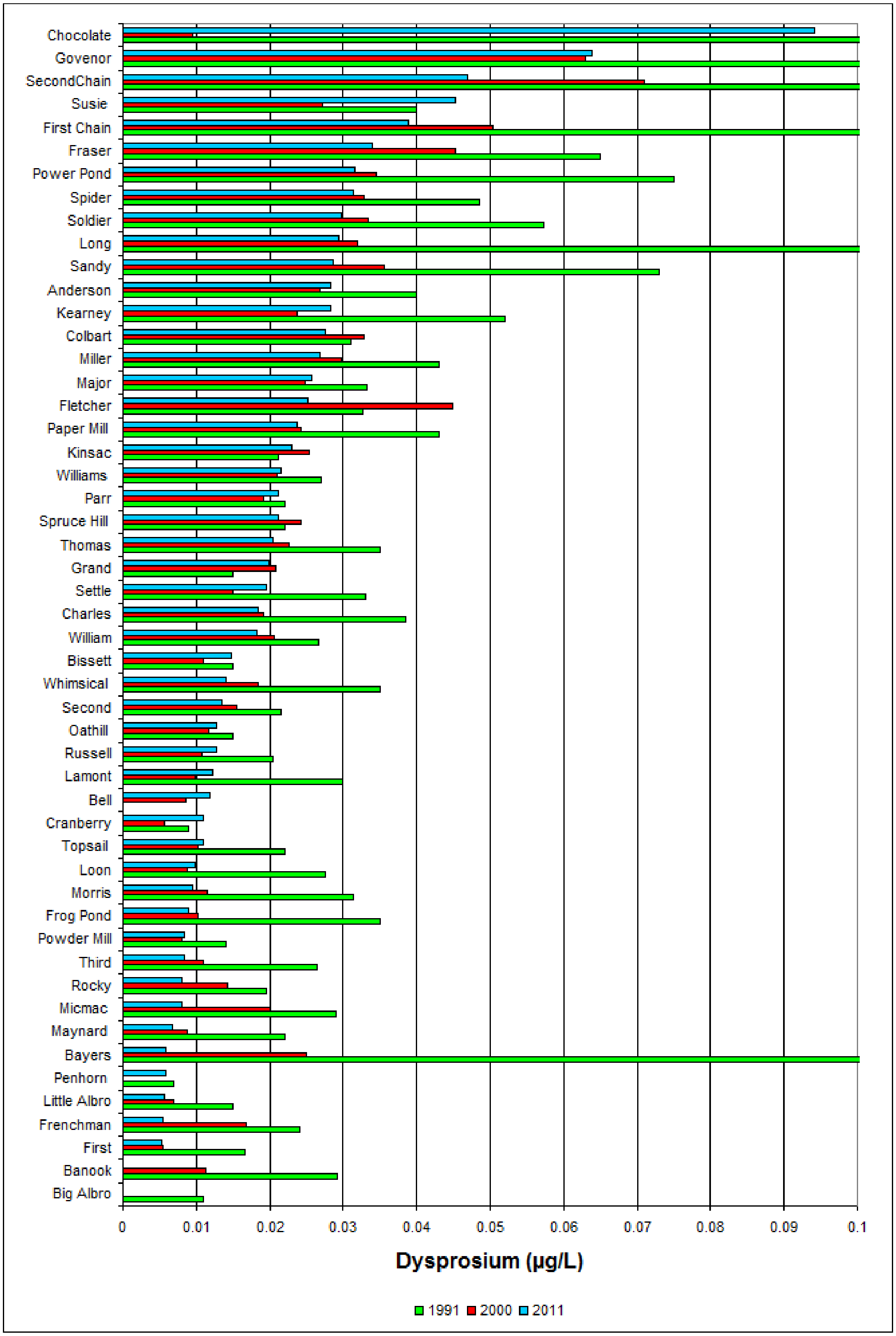

Figure 43. Dysprosium concentrations.

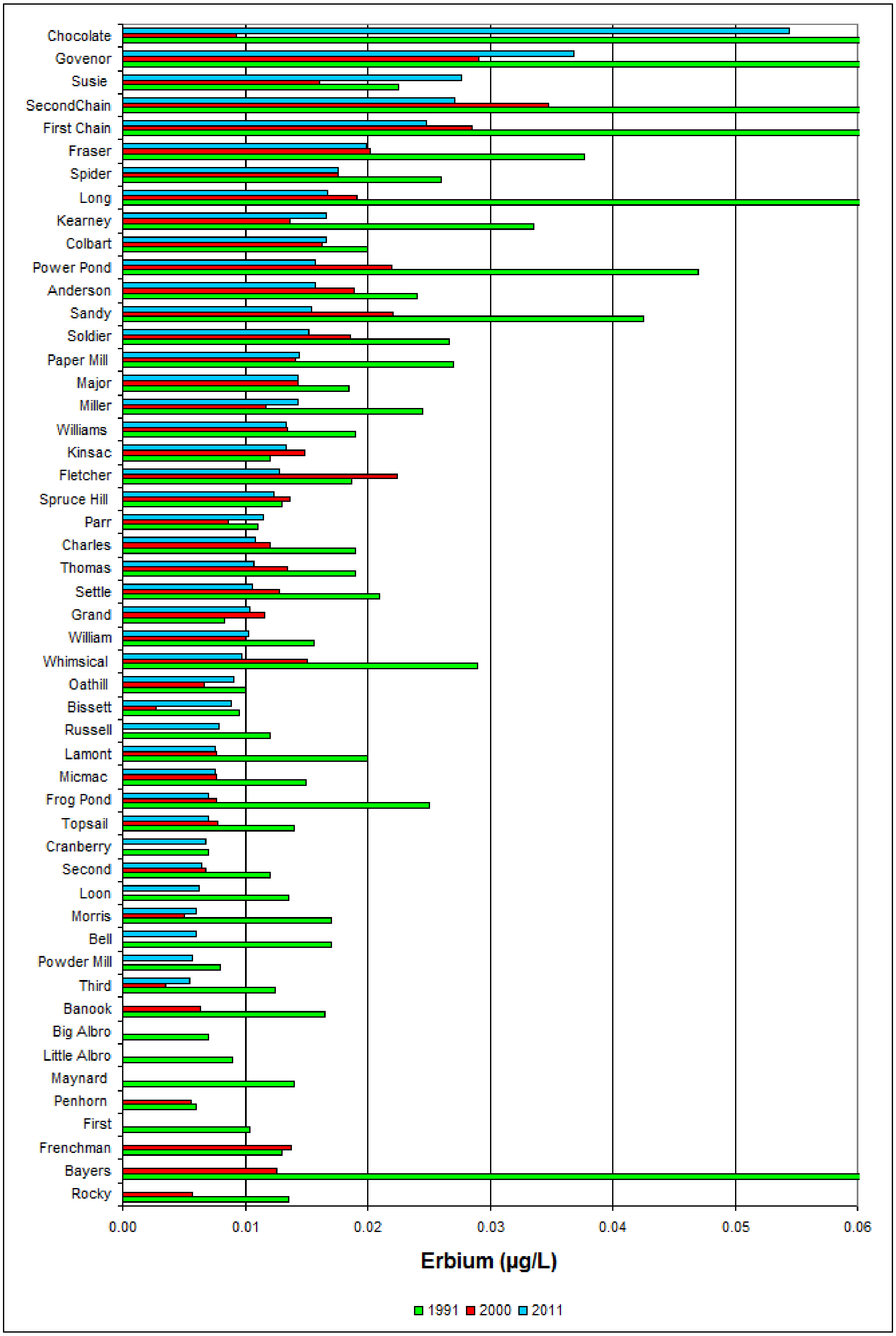

Figure 44. Erbium concentrations.

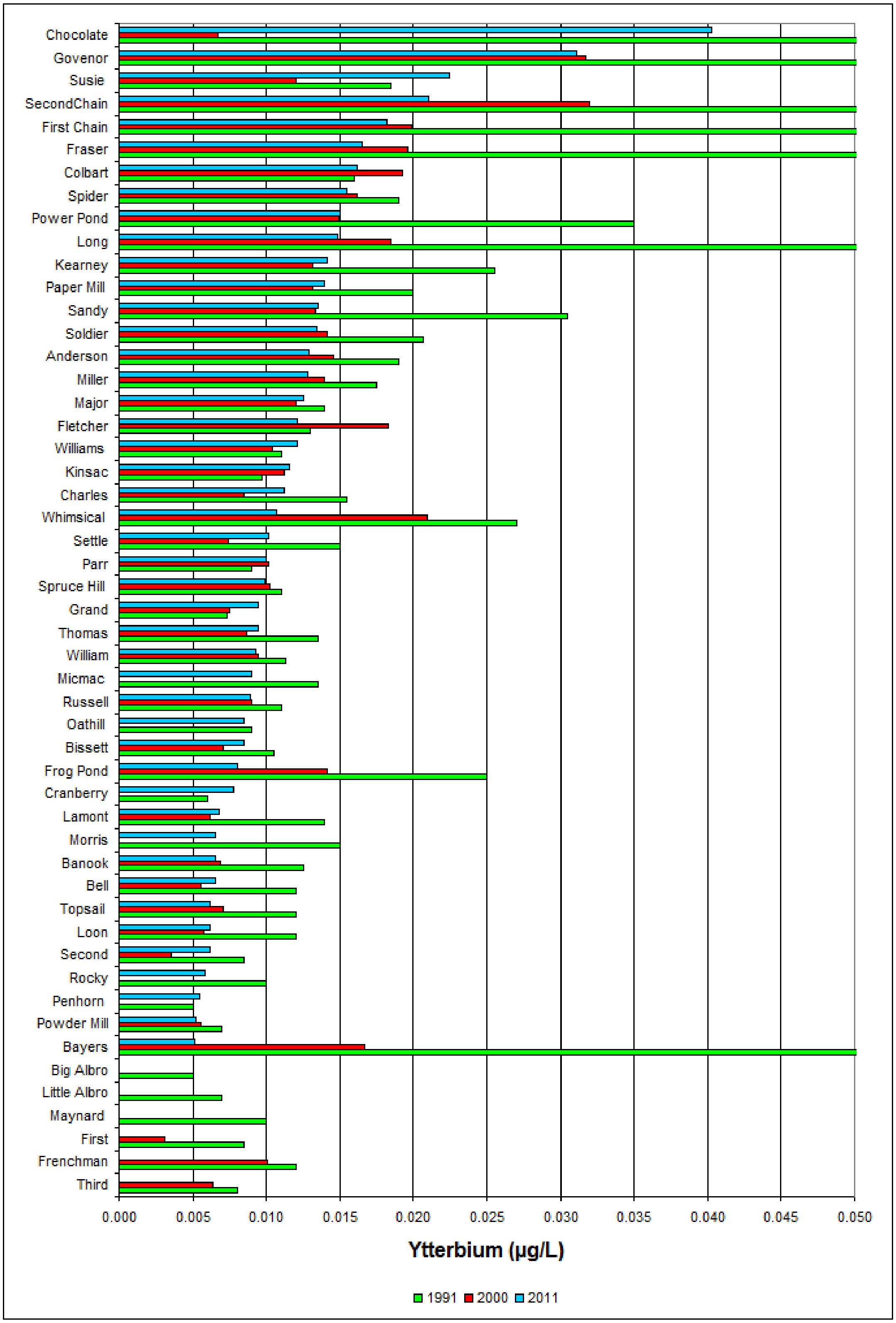

Figure 45. Ytterbium concentrations.

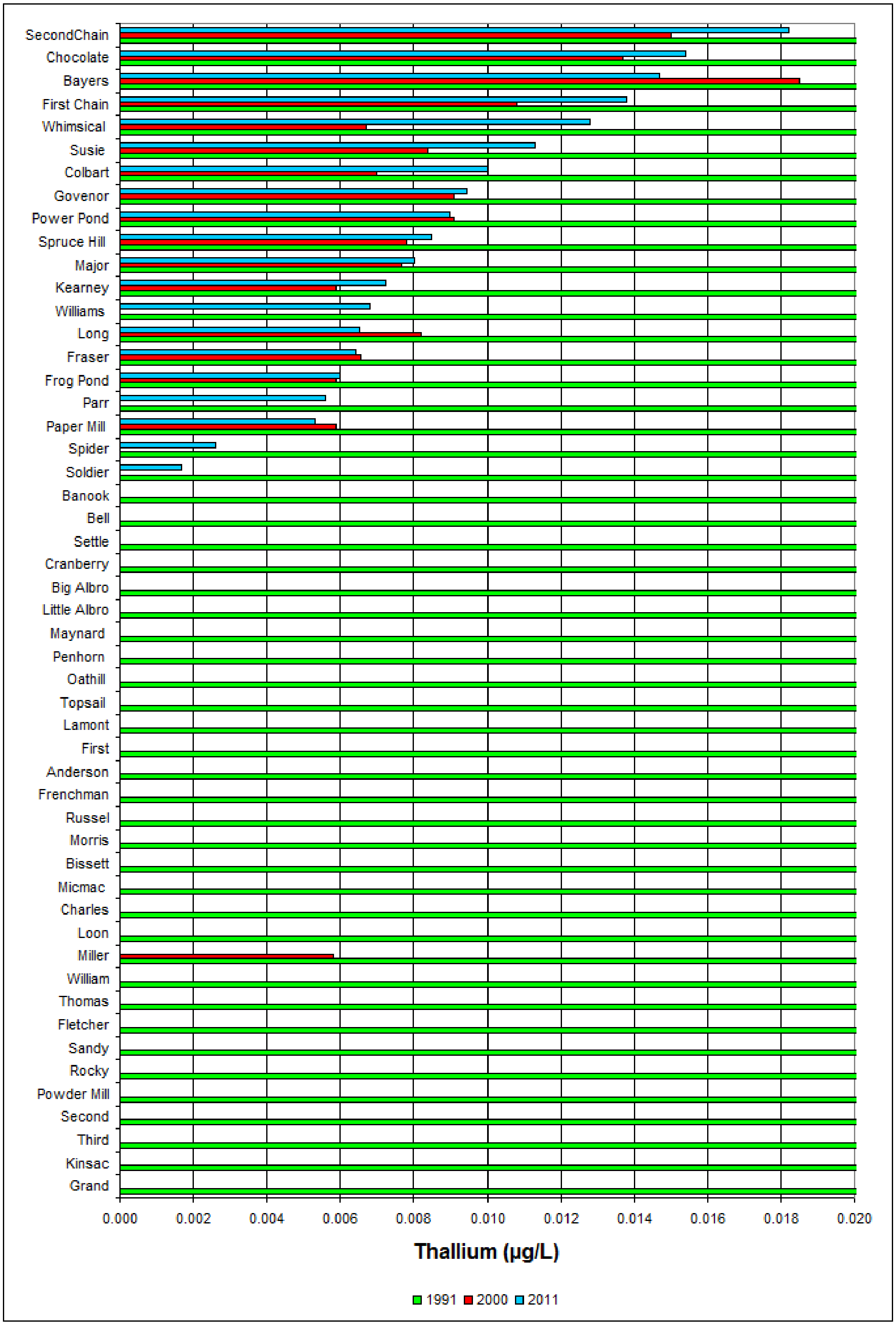

Figure 46. Thallium concentrations.

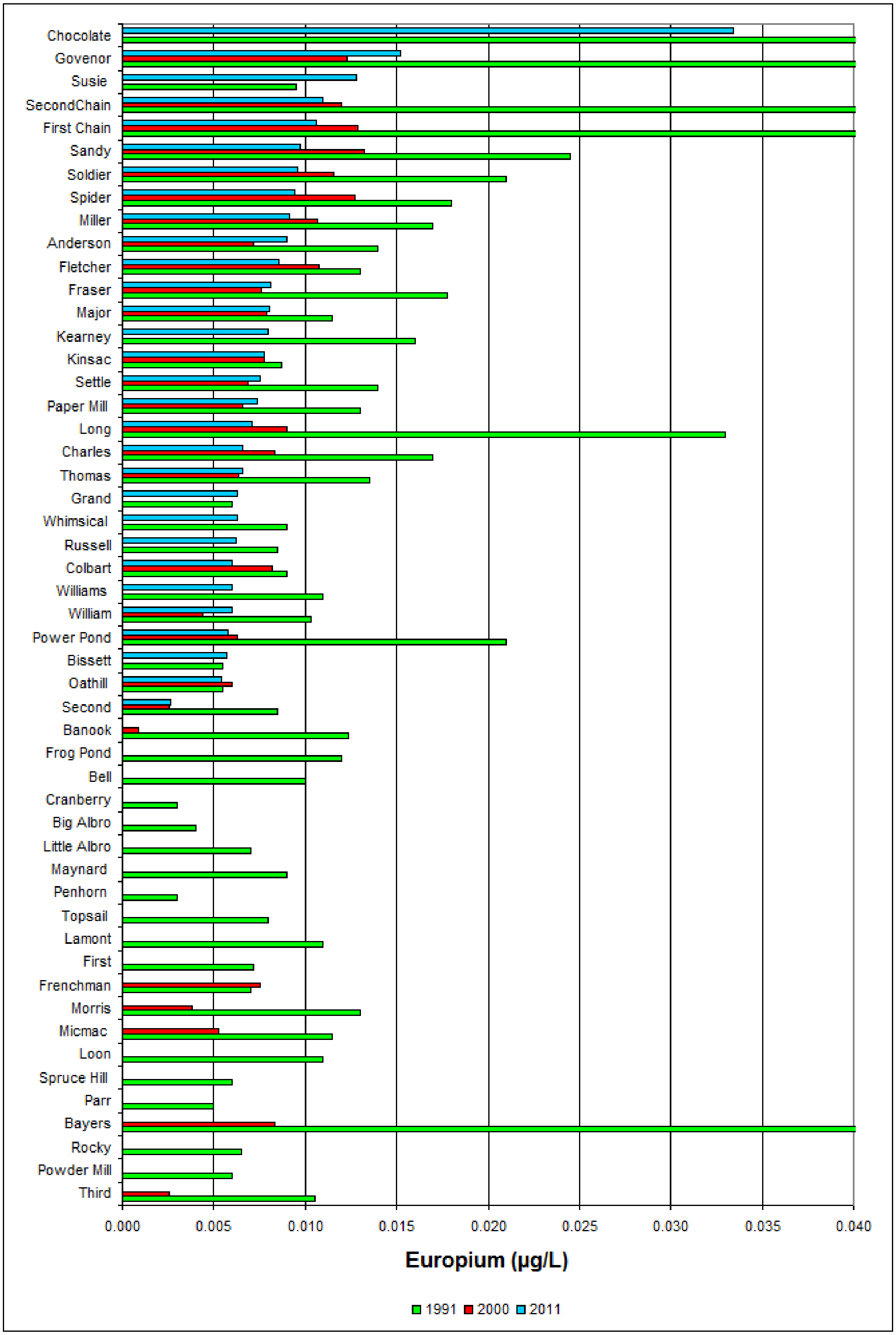

Figure 47. Europium concentrations.

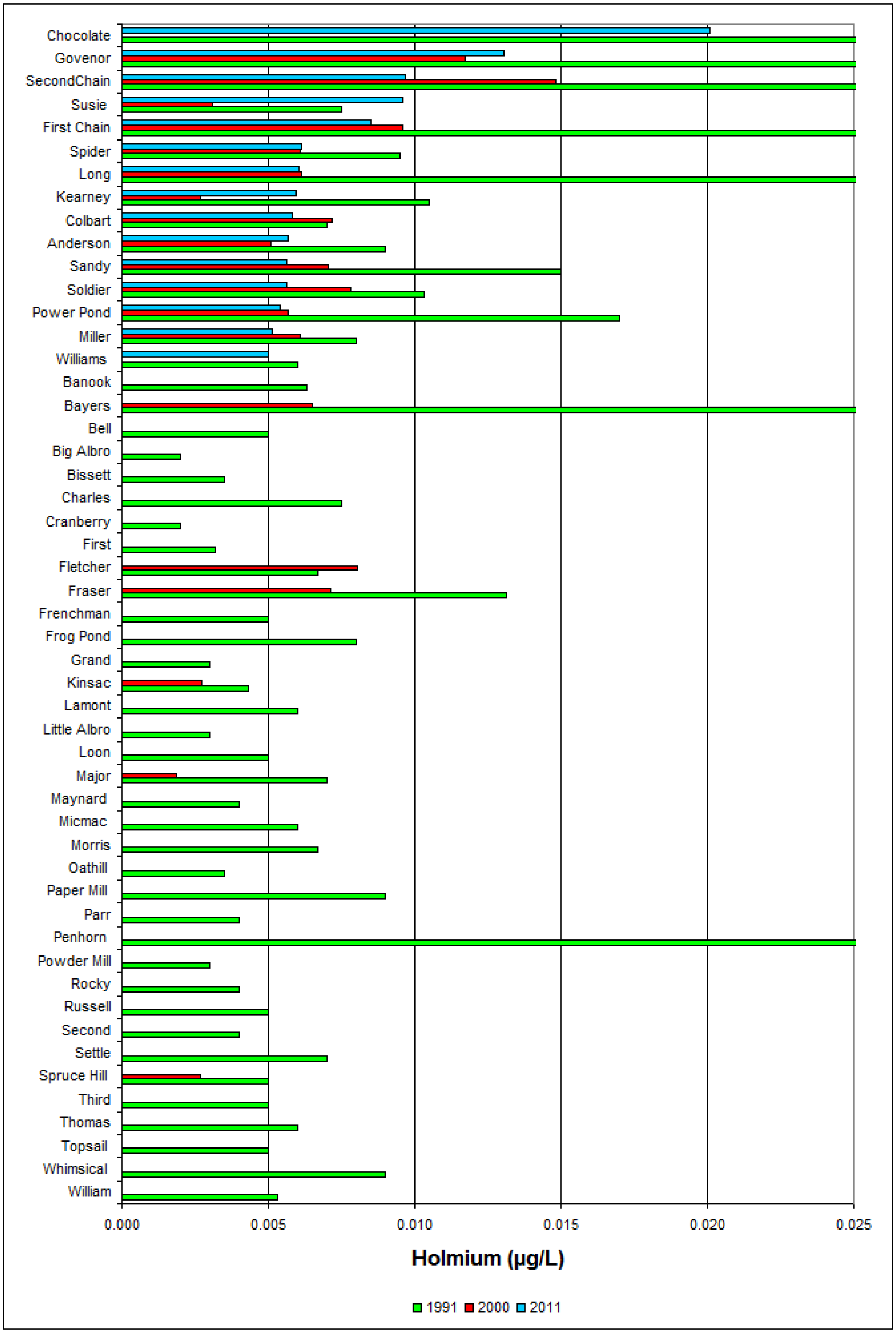

Figure 48. Holmium concentrations.

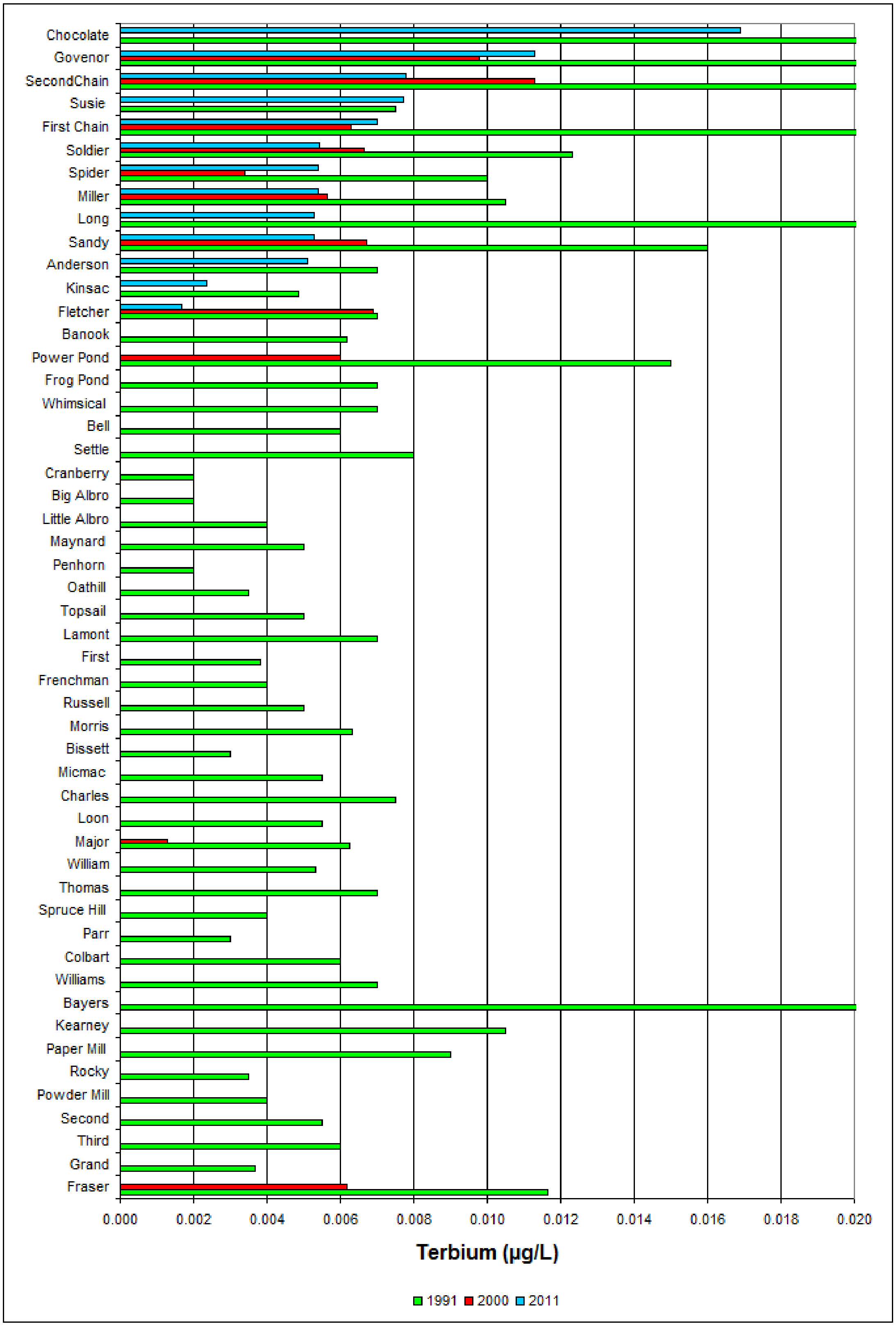

Figure 49. Terbium concentrations.

DISCUSSION

This long-term synoptic sampling program has collected water quality data from 51 Halifax-area lakes (Figure 1) at decadal intervals (1980, 1991, 2000 and 2011). Variables measured included pH, major ions, nutrients, organic matter and trace elements. With just a few exceptions, the lakes sampled and variables measured were constant over this 31-year period which makes this sampling program rather unique. The resulting dataset provides an excellent basis for assessing overall water quality, identifying environment concerns and exploring possible long-term trends.

It should be noted that the extent of development has increased markedly in the watersheds of some of the lakes sampled over the 31-year observation period. Examples are Frenchman Lake in Burnside Industrial Park and Whimsical Lake in Spryfield. Changes in water quality can therefore be expected in these lakes, and pronounced increases in conductivity have in fact been observed in both lakes (Figure 5). However, some of the other lakes sampled have remained relatively protected from the impacts of human activity over the period of observation so major changes in their water quality are not expected. Examples are Spider Lake, Lake Major, Spruce Hill Lake and Anderson Lake. In addition, other lakes had well-developed watersheds when the surveys began in 1980 and have changed little over the intervening years. Examples include Lake Banook, Maynard Lake and Oathill Lake.

LONG-TERM TRENDS

Clear trends of increasing mean concentration with time are evident for conductivity, sodium, calcium, magnesium, potassium, chloride, alkalinity and nitrate (Table 4). Except for 2000, there also appeared to be a trend of increasing concentration of total nitrogen. The increases in the mean concentrations of these eight variables between 1980 (or 1991) and 2011 were statistically significant (Table 5). While there were some significant differences in the mean concentrations of the other variables between certain sampling periods (Table 5), consistent trends of increasing concentrations with time were not observed. It should be noted that these significant decadal increases are more apparent in some lakes than others, especially those in watersheds that have been subjected to higher levels of human activity. These increases are due to the widespread use of water-soluble chemicals such as road salt (sodium chloride), agricultural lime (calcium carbonate) and fertilizers (phosphorus and nitrogen).

Overall, the nutrient levels in Halifax-area lakes continue to remain relatively low and only a few lakes appear to have high values for trophic state index (Figure 23). Chlorophyll concentrations also remain relatively low at the time of the spring turnover but can be expected to increase during the summer. Halifax-area lakes do not receive raw sewage directly but can be affected by occasional overflow events from combined sewers or pumping stations during major rain events, improper connections or faulty septic fields.

Other recent studies in Halifax-area lakes have detected additional significant changes over time in water quality variables. Decreases in pH due to acid precipitation have been well documented (Watt et al. 1979, Tropea et al. 2007). Recent monitoring data suggest that international controls on sulphate emissions are having a positive effect and that some Nova Scotian lakes are beginning to show signs of recovery from acidification (Clair et al. 2003, 2007). Anderson et al. (2017) examined sulphate deposition in Pockwock Lake and Lake Major from 1999 to 2015. Both of these lakes are protected surface water supplies for Halifax. They observed that sulphate deposition decreased by 68% while there was a corresponding increase in pH of 0.1-0.4 units over the 16-year period. Increases in pH can also be brought about by removing naturally occurring acidic terrestrial habitats in watersheds, such as acid bogs, and adding alkaline contaminants such as carbonate, the major component of lime which is extensively applied to lawns and gardens.

Evidence for changes in lake water quality over time has also come from recent studies using lake sediments. Ginn et al. (2015) used a rapid paleolimnological approach based on diatom assemblages in sediment cores to evaluate the impacts of acidification, nutrient input, deicing salt and climate change. This approach was applied to the same 51 lakes included in the synoptic surveys. All lakes have experienced floristic changes in diatom species composition since pre-disturbance times but different environmental stressors are implicated. Eight lakes demonstrated significant decreases in pH, eight lakes demonstrated significant increases in total phosphorus, 22 lakes demonstrated increases in salt while 19 relatively pristine lakes showed changes in diatoms linked to climate warming. Dunnington et al. (2018) have used X-ray fluorescence technology to study evidence of watershed-scale disturbance in the bulk geochemical properties of sediment cores from eight Halifax-area lakes. Using this technology, they observed evidence of deforestation activities in the sediments in Lake Major and Pockwock Lake, both municipal water supplies, and the evidence of urbanization in the sediments of Lake Fletcher, Lake Lamont and First Lake.

COMPARISON TO WATER QUALITY GUIDELINES

One way of assessing the significance of the concentrations observed in these surveys is to compare them to guidelines for assessing the water quality of aquatic ecosystems, for example those developed by the Canadian Council of Ministers of the Environment (CCME) (CCME 1999). The available guidelines for the protection of freshwater aquatic life are listed in Table 7. These guidelines are based on the total concentration of a substance in an unfiltered sample while the concentrations presented in this report are for filtered samples and will tend to be lower for particle-reactive elements. Applying these values to our dataset, it appears that more than two-thirds of the lakes sampled have a pH below the preferred range (Figure 4), about one third of the lakes have chloride levels above the guideline (Figure 11) but only a few lakes have values of total nitrogen above the guideline (Figure 18). The nitrate and total phosphorus values are all below the guidelines (Figures 15 and 19). Approximately 20 lakes appear to have zinc concentrations exceeding the guideline (Figure 29). With the exception of Lake Charles,

Table 7. CCME water quality guidelines for the protection of freshwater aquatic life.

Variable	CCME Guideline
Arsenic	5 µg/L
Cadmium	0.09 µg/L
Chloride	120 mg/L
Iron	300 µg/L
Nitrate	3.0 mg/L
pH	6.6 to 9.0
Total N	1.0 mg/L
Total P	0.05 mg/L
Uranium	15 µg/L
Zinc	7 µg/L

all lakes have arsenic concentrations below the guideline (Figure 30) and all lakes have iron and uranium concentrations below the guidelines (Figures 25 and 39). Therefore, with the exception of pH, chloride, total nitrogen, zinc and arsenic in certain lakes, the available CCME guidelines suggest that the existing water quality in the Halifax-area lakes sampled poses no threat to the protection of aquatic life.

Stantec (2012) reported that aluminum and iron consistently failed to meet the CCME guidelines in all lakes. However, it is well recognized that because of the bedrock geology their natural background levels are elevated in Nova Scotian lakes compared to the rest of the country. Stantec (2012) also reported that cadmium consistently exceeded the guideline in all lakes.

COMPARISON WITH HRM WATER QUALITY MONITORING PROGRAM

It is most interesting and valuable to compare the results of this synoptic survey program with those obtained by the HRM Water Quality Monitoring Program (Stantec 2012). This program was initiated in the spring of 2006 and ran until 2011. Each year, surface water samples were collected by HRM staff during the spring, summer and fall from over 52 lakes in the Halifax-area. Subsurface water samples were collected at consistent locations near the centre of each lake and a similar suite of water quality variables (except trace elements) was measured using standard methods by Stantec Consulting Ltd. (Stantec 2012). Thirty-six of the lakes included in this program were also sampled in the synoptic surveys (Table 8).

The mean concentrations of the fourteen common variables observed in same thirty-six lakes during the spring of 2011 are compared in Table 9. These datasets are not strictly comparable because of differences in sampling date (HRM samples were collected a few weeks later), location within the lake and methods. The mean concentrations observed in the HRM Water Quality Monitoring Program were slightly higher for most variables except for chlorophyll and DOC which were slightly lower. Nevertheless, overall there is good agreement which gives confidence in the accuracy and comparability of the two datasets.

Stantec (2012) estimated the trophic state of lakes sampled in the HRM Water Quality Monitoring Program using the CCME Canadian Guidance Framework for phosphorus (CCME 2004). Using total phosphorus concentrations in surface waters, this procedure assigns a given lake to one of the general categories of trophic state. They reported that 22% of the lakes sampled were categorized as oligotrophic, 58% as mesotrophic, 12% as meso-eutrophic, 7% as eutrophic and 1% as hypertrophic. The categorization of the 36 lakes sampled in common with our synoptic surveys is shown in Table 10 along with the mean concentration of total phosphorus. As expected, the relative ranking of the lakes is very similar to the results of our TSI calculations (Figure 23). Settle, Bissett and Frenchman lakes ranked high in both indices (i.e. eutrophic) while Chocolate, Paper Mill and Kearney ranked low in both (i.e. oligotrophic).

Stantec (2012) also calculated a water quality index following CCME procedures and the guidelines for the protection of aquatic life (Table 7). The index values are based on the frequency of water quality guidelines exceeded, the percentage of measurements which exceeded one or more of the guidelines and the intensity of guideline exceedances. The value of the index ranges from 0 to 100, the higher the index the better the water quality. Values calculated for the lakes sampled in the HRM Water Quality Monitoring Program ranged from 45 to 90 and 41% of the lakes were categorized as having good water quality, 54% as fair and only 6% as marginal. The values for the thirty-six lakes sampled by both the synoptic surveys and the HRM Water Quality Monitoring Program are listed in Table 11. The lowest values (i.e. poorest water quality) were observed in Chocolate, First Chain and Governor lakes while the highest values (i.e. best water quality) were observed in Maynard, Second, Thomas, First, Little Albro, William, Big Albro and Third lakes.

Such a water quality index is not the same as a trophic state index (Table 10) and therefore the relative ranking of lakes is quite different. As emphasized by Carlson (1977), the term 'water quality' implies a subjective judgement and depends on the intended use of the water and the local attitudes of the people. Therefore, it is best kept separate from the concept of trophic state which should remain neutral to such subjective judgments.

Possible temporal trends within a subset of 17 water bodies sampled by HRM at similar times of the year in their water quality study between 2006 and 2011 were examined by Stantec (2012). Eleven of these lakes have also been sampled during the synoptic surveys. Governor, Kearney, Loon and Williams lakes appeared to show a slight decrease of pH over the five-year period while no apparent trends were obvious in the nitrate data. Governor, Micmac, Morris and Williams lakes showed a slight increase in total phosphorus while Banook, Charles, Governor, Morris, Russell and Williams lakes showed slight increases in chlorophyll. An increase in sodium was observed in Lake Charles while decreases were observed in Banook, Governor and Kearney. Apparent decreases in chloride were observed in Banook and Governor.

There is not complete agreement between the temporal trends observed in the two programs. Both did show an increase in sodium and chloride concentrations with time. However, the synoptic survey data indicate a significant increase of nitrate with time which was not seen in the HRM data but did not reveal any significant temporal trends in pH, total phosphorus or chlorophyll as observed in the HRM data. These differences can perhaps be partially explained by the different time periods examined. The HRM study covered a period of only six years while the synoptic surveys have so far covered a period of 31 years. There also was a substantial difference in the number of lakes included in each analysis (11 versus 51).

Table 8. Lakes sampled by both the synoptic survey and the HRM Water Quality Monitoring Program in the spring of 2011.

Big Albro Lake	Loon Lake
Lake Banook	Maynard Lake
Bell Lake	Lake Micmac
Bissett Lake	Morris Lake
Lake Charles	Oathill Lake
Chocolate Lake	Paper Mill Lake
Cranberry Lake	Penhorn Lake
First Lake	Powder Mill Lake
First Chain Lake	Rocky Lake
Fletcher Lake	Russell Lake
Frenchman Lake	Sandy Lake
Frog Pond	Settle Lake
Governor Lake	Second Lake
Grand Lake	Third Lake
Kearney Lake	Lake Thomas
Lake Kinsac	Whimsical Lake
Little Albro Lake	Lake William
Long Lake	Williams Lake

Table 9. Comparison of the mean concentrations of water quality variables observed in the thirty-six lakes listed in Table 8 during the 2011 synoptic survey and HRM Water Quality Monitoring Program in the spring of 2011.

Variable	Units	Synoptic Survey	HRM Program
pH	Standard Units	6.23	6.58
Conductivity	µS/cm	374.1	463.2
Sodium	mg/L	57.4	70.6
Calcium	mg/L	10.1	12.0
Magnesium	mg/L	1.4	1.6
Potassium	mg/L	1.2	1.3
Chloride	mg/L	91.2	113.4
Sulphate	mg SO_4/L	12.1	14.3
Alkalinity	mg $CaCO_3$/L	9.1	17.1
Total N	mg N/L	0.35	0.54
Total P	mg P/L	0.005	0.010
Chlorophyll	µg/L	2.1	1.8
DOC	mg/L	3.	3.34
Colour	TCU	23.8	23.7

Table 10. The trophic state categorization of the thirty-six lakes sampled in both the synoptic surveys and HRM Water Quality Monitoring Program as determined by Stantec (2012) using CCME procedures (CCME 2004) and mean total phosphorus concentrations as measured in the HRM Water Quality Monitoring Program.

Lake	Total Phosphorus (mg/L)	Category
Settle Lake	0.029	Meso-Eutrophic
Bissett Lake	0.027	Meso-Eutrophic
Frenchman Lake	0.022	Meso-Eutrophic
Oathill Lake	0.020	Mesotrophic
Cranberry Lake	0.020	Mesotrophic
Frog Pond	0.016	Mesotrophic
Rocky Lake	0.016	Mesotrophic
Governor Lake	0.016	Mesotrophic
Loon Lake	0.015	Mesotrophic
Sandy Lake	0.015	Mesotrophic
Bell Lake	0.015	Mesotrophic
Morris Lake	0.014	Mesotrophic
Whimsical Lake	0.014	Mesotrophic
Lake Thomas	0.013	Mesotrophic
Maynard Lake	0.013	Mesotrophic
Kinsac Lake	0.012	Mesotrophic
Little Albro Lake	0.012	Mesotrophic
Penhorn Lake	0.012	Mesotrophic
Second Lake	0.012	Mesotrophic
Russell Lake	0.011	Mesotrophic
Lake Charles	0.011	Mesotrophic
Lake Banook	0.011	Mesotrophic
First Lake	0.011	Mesotrophic
Lake Micmac	0.010	Oligotrophic
Power Mill Lake	0.010	Oligotrophic
Big Albro Lake	0.010	Oligotrophic
Third Lake	0.009	Oligotrophic
Lake William	0.009	Oligotrophic
Williams Lake	0.009	Oligotrophic
Lake Fletcher	0.009	Oligotrophic
Long Lake	0.009	Oligotrophic
Grand Lake	0.009	Oligotrophic
Chocolate Lake	0.007	Oligotrophic
Paper Mill Lake	0.007	Oligotrophic
Kearney Lake	0.007	Oligotrophic
First Chain Lake	0.007	Oligotrophic

Table 11. Water quality index calculated by Stantec (2012) for the thirty-six lakes sampled in both the synoptic surveys and HRM Water Quality Monitoring Program using CCME procedures and the available guidelines for the protection of aquatic life.

Lake	Water Quality Index	Category
Chocolate Lake	67	Fair
First Chain Lake	68	Fair
Governor Lake	68	Fair
Frog Pond	70	Fair
Whimsical Lake	70	Fair
Frenchman Lake	70	Fair
Russell Lake	70	Fair
Bissett Lake	77	Fair
Long Lake	78	Fair
Settle Lake	78	Fair
Penhorn Lake	78	Fair
Sandy Lake	79	Fair
Lake Banook	79	Fair
Loon Lake	79	Fair
Oathill Lake	80	Good
Cranberry Lake	80	Good
Lake Micmac	80	Good
Williams Lake	80	Good
Morris Lake	80	Good
Kearney Lake	80	Good
Bell Lake	80	Good
Grand Lake	80	Good
Lake Charles	80	Good
Lake Fletcher	81	Good
Kinsac Lake	81	Good
Powder Mill Lake	81	Good
Rocky Lake	89	Good
Paper Mill Lake	89	Good
Maynard Lake	90	Good
Second Lake	90	Good
Lake Thomas	90	Good
First Lake	90	Good
Little Albro Lake	90	Good
Lake William	90	Good
Big Albro Lake	90	Good
Third Lake	90	Good

SURVEY LIMITATIONS

In evaluating the data collected in these synoptic surveys, it should be noted that the data represent only snapshots taken at one time during the seasonal cycle at decadal intervals. In addition, it should be emphasized that these periodic synoptic surveys have not measured all the important water quality variables that are needed to understand the health of lake ecosystems and their suitability for wildlife and recreational use. Due to the limitations of time, personnel and funding, analyses have been restricted to those variables that can be conveniently measured in 2 L of surface water. Important variables not measured include suspended sediment, dissolved oxygen and microorganisms. Another limitation is that sampling has been restricted to the period of assumed spring turnover when the lakes are well-mixed from top to bottom and has not included any measurements in deep water which are particularly important during the summer months when lakes are stratified. In addition, the data collected in these synoptic surveys do not provide information on other potential environmental issues of concern such as changes in the species composition of biological communities, contaminants in sediments, phosphorus loading, algal blooms and rooted aquatic vegetation.

This, the fourth in a series of lake water quality surveys over a period of 31 years, is only one of many contributions to the scientific knowledge that is necessary to understand the mechanisms that affect that affect the water quality of Halifax-area lakes. Fortunately, other more detailed studies addressing important issues have been recently conducted (e.g. Stantec 2012, Ginn et al. 2015, Tarr and White 2015, Anderson et al. 2017 and Dunnington et al. 2018). These investigations are being carried out by a variety of organizations including government agencies, consultants, universities, students and numerous citizen environmental groups that have been formed. Some additional examples are as follows.

For many years, municipalities have monitored the concentrations of coliform bacteria in the water at recreational beaches. Beaches are temporarily closed when observed levels exceed guidelines for safe recreational use, usually as a result of over use, and remain so until concentrations return to acceptable levels. The frequency of closures has increased in some lakes in recent years, in particular at Birch Cove Beach on Lake Banook in Dartmouth. This monitoring is ongoing. The HRM Water Quality Monitoring Program also included bacterial sampling (Stantec 2012).

Recent years have also seen an increase in the abundance of aquatic weeds and the occurrence of blue-green algae in some Halifax-area lakes. Both of these plant forms occur naturally but their growth can be stimulated by nutrient enrichment. These increases have been particularly pronounced in Lakes Banook and Micmac in Dartmouth and have had a major impact on recreational use and competitive paddling. High concentrations of blue-green algae have resulted in some closures of recreational beaches. Halifax funded a program to monitor and harvest aquatic weeds in these lakes during the summer months from 2015-2018. It also funded a pollution control study of Lakes Banook and Micmac with a focus on understanding bacterial loading in order to reduce the frequency of beach closures in the future.

Another emerging issue has been the development of anoxic conditions in the deep water of some lakes, particularly during the summer months when lakes are stratified. While these can occur naturally, their increasing frequency and magnitude is cause for concern. Oxygen profile measurements by citizen environmental groups have clearly demonstrated the occurrence of periodic anoxic events in Oathill and Penhorn lakes in the summer months. In order to mitigate these events, under the lead of these groups, a solar-powered aerator was installed in Oathill Lake in 2015 and a second one is scheduled to be installed in Penhorn Lake in 2019.

As result of expanding development west of Bedford, Halifax has recently commissioned watershed studies of Sandy and Papermill Lakes (AECOM 2014 and Centre for Water Resource Studies 2016) in order to assist watershed management and future land use development in the area. These reports provide considerable water quality data and analysis. Another recent study of interest is a detailed examination of the phosphorus loading and trophic state of Fletcher Lake by a Dalhousie graduate student (Poltarowicz 2017). Extensive field measurements were used to quantify the various sources and sinks of phosphorus in the watershed. Export coefficients were calculated for different categories of land use and it was concluded that the lake could continue to be categorized as oligotrophic.

LOOKING AHEAD

There are good reasons for repeating this synoptic survey in 2020 if the necessary leadership and resources can be organized. With a modest financial investment by governments at all levels and the assistance of numerous organizations and volunteers, this valuable dataset of important water quality variables in Halifax-area lakes can be extended. The cumulative data can be used in many ways including comparing the general environmental properties of different lakes, examining the possibility of trends over decadal intervals and identifying the emerging environmental issues that should be investigated with more detailed studies.

There is considerable merit in maintaining consistency in the design of the sampling program to increase the chances of observing long-term trends. It would be desirable to continue sampling the same 51 lakes, even though some may not be showing any significant changes at the present time for it is hard to predict the future. If there is need to drop some lakes from future surveys, these should be some of the more isolated lakes located in undeveloped watersheds. Consideration could be given to adding a few additional lakes. Examples include Pockwock Lake, which along with Lake Major is a major source of water for Halifax, and Cox Lake in Hammonds Plains which is part of the proposed Blue Mountain Birch Cove Wilderness Park and experiencing increased development in its watershed.

There is general agreement that total phosphorus and chlorophyll are key variables to continue measuring since increasing values are an indicator of increasing eutrophication and cause for concern. The highest concentrations of these two variables in the synoptic surveys were found in Settle, Parr, Oathill, Rocky, Power Pond, Russell, Powder Mill, Bissett and Penhorn lakes. Stantec (2012) recommended eleven Halifax-area lakes as high priority for continued water quality monitoring. All but one of these (McCabe Lake) have been sampled in the synoptic surveys. These are Morris, Russell, Paper Mill, Kearney, Loon, Charles, Banook, Micmac, Williams and Fletcher. As reported in Stantec (2012), HRM has already identified six high priority lakes as part of its regional planning process. These lakes, all included in the synoptic surveys, are Big Albro, Banook, Little Albro, Maynard, Oathill and Penhorn. Clearly all the above-mentioned lakes should be included in possible future synoptic surveys and more discussion needed before any changes are made in survey design.

It must be kept in mind that these synoptic surveys are only a part of the total spectrum of water quality monitoring programs that are needed to ensure the well-being of Halifax-area lakes over the long term. Other studies should be lake or watershed specific, have a more detailed spatial and temporal sampling design, cover all seasons of the year, include profiling the entire water column and measure other important variables including oxygen. These studies should focus on lakes undergoing development pressures which are more likely to experience changes in water quality. Coordination and funding from all levels of government is essential.

While the impacts of human activity can be found in most Halifax-area lakes, the results of this and other studies indicate that the water quality generally remains at a relatively good level. With the possible exception of low pH levels in some lakes, there seem to be no appreciable concerns regarding the protection of aquatic life. However, there are increasing concerns regarding recreational use in certain lakes because of the recent proliferation of rooted aquatic vegetation, coliform bacteria and blue-green algae. Major management issues will continue to be limiting the input of nutrients, in particularly phosphorus, and promoting the recovery of lakes from decades of acid precipitation. This will require a well-coordinated program, led by all levels of government but involving all interested partners, including general monitoring programs, site-specific studies and mitigative measures. Our Halifax-area lakes are priceless assets of great value and worthy of protection for today and future generations.

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APPENDIX 1a. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	Anderson (68)	Banook (69,70)	Bayers (25)	Bell (82)	Big Albro (79)	Bissett (60, 61)	Charles (56, 57)	Chocolate (83)	Colbart (32)	Cranberry (80)
pH	5.21	7.36	5.74	5.66	7.05	7.19	6.70	5.24	6.20	7.07
Alkalinity (mgCaCO3/L)	0.9000	24.0750	0.9000	2.4000	9.2000	24.8000	14.8500	7.7450	1.8000	18.4000
Aluminum (mg/L)	0.1240	0.0170	0.0690	0.0860	0.0160	0.1040	0.0400	0.0530	0.2350	0.0770
Ammonia (mg/L)	0.0054	0.0056	0.0134	0.0100	0.0056	0.0126	0.0062	0.0213	0.0055	0.0138
Calcium (mg/L)	2.00	20.58	16.90	2.50	9.80	20.10	9.85	12.95	8.00	15.70
Chloride (mg/L)	14.2	175.0	218.0	14.6	109.0	209.3	55.4	128.3	118.9	140.5
Chlorophyll (µg/L)	2.2	1.1	1.0	0.8	1.0	3.6	1.1	0.1	1.3	2.9
Colour (TCU)	25.6	32.1	5.3	9.4	8.5	24.9	12.8	12.6	42.3	15.0
Conductivity (µS/cm)	48.73	711.75	817.00	75.80	433.00	826.50	257.00	644.00	463.00	574.00
Diss. Organic Carbon (mg/L)	4.10	2.25	1.80	2.40	2.30	3.60	2.90	2.15	5.20	2.60
Magnesium (mg/L)	0.50	2.15	2.80	1.20	1.10	2.60	1.45	1.70	1.00	2.30
Nitrate (mgN/L)	0.0177	0.2856	0.0207	0.1074	0.0516	0.3613	0.4389	0.2372	0.2113	0.4962
Phosphate (mgP/L)	<0.001	0.00212	<0.001	<0.001	0.00175	0.00354	0.00210	0.00126	0.00091	0.00301
Potassium (mg/L)	0.50	1.68	1.60	0.80	0.80	1.80	1.35	1.30	1.10	1.60
Silica (mgSi/L)	0.0312	0.5244	0.0311	0.1054	0.3479	0.5236	0.9957	0.2181	0.0978	0.1049
Sodium (mg/L)	8.20	103.95	124.80	7.90	64.10	128.10	33.20	76.10	70.30	85.00
Sulphate (mgSO4/L)	4.3	19.5	25.2	5.2	10.7	17.4	10.1	22.0	13.0	14.0
Temperature (°C)	4.00	6.00	6.00	4.00	4.00	5.00	3.50	5.00	5.00	6.00
Total Nitrogen (mgN/L)	0.140	0.423	0.100	0.260	0.190	0.635	0.580	0.325	0.420	0.720
Total Phosphorus (mgP/L)	0.0030	0.0035	0.0030	0.0060	0.0030	0.1450	0.0050	0.0035	0.0070	0.0080

APPENDIX 1b. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	First (71,72)	First Chain (27)	Fletcher (35-37)	Fraser (23, 24)	Frenchman (67)	Frog Pond (85)	Governor (21, 22)	Grand (1-3)	Kearney (17, 18)	Kinsac (4-6)
pH	7.10	4.84	6.59	5.70	6.78	6.82	6.18	6.47	6.13	6.07
Alkalinity (mgCaCO3/L)	25.9500	-0.4000	7.2000	1.3000	9.2000	16.5000	2.9500	5.1000	2.8000	3.9333
Aluminum (mg/L)	0.0375	0.4900	0.0987	0.2245	0.0270	0.0440	0.2770	0.0803	0.2080	0.1647
Ammonia (mg/L)	0.0115	0.0072	0.0381	0.0080	0.0266	0.0137	0.0452	0.0173	0.0120	0.0088
Calcium (mg/L)	16.55	5.10	5.90	2.25	22.70	19.40	11.10	4.90	6.30	3.83
Chloride (mg/L)	126.1	91.6	33.7	17.2	349.4	160.7	123.4	19.4	55.7	19.9
Chlorophyll (µg/L)	3.1	0.8	1.2	1.4	1.9	0.6	2.4	0.7	0.5	0.8
Colour (TCU)	12.5	5.3	28.7	47.2	17.4	13.4	41.0	24.9	31.0	33.6
Conductivity (µS/cm)	528.50	364.00	160.33	80.80	1290.00	673.00	494.50	105.33	231.50	97.00
Diss. Organic Carbon (mg/L)	2.55	1.00	4.30	6.30	3.00	2.90	4.10	4.40	4.10	4.67
Magnesium (mg/L)	2.00	1.10	0.90	0.70	2.10	2.10	1.80	0.80	1.20	0.80
Nitrate (mgN/L)	0.1660	0.0161	0.2425	0.0897	0.1700	0.1838	0.3513	0.1131	0.2152	0.1020
Phosphate (mgP/L)	0.00319	<0.001	0.00071	0.00130	0.00119	0.00186	0.00123	<0.001	<0.001	0.00056
Potassium (mg/L)	1.60	0.70	1.03	0.80	1.70	1.80	1.25	0.77	0.80	0.73
Silica (mgSi/L)	0.4204	0.4112	0.3388	0.0503	0.0199	0.0694	0.1889	0.1815	0.1929	0.1611
Sodium (mg/L)	77.40	57.20	20.70	9.55	360.50	97.70	76.45	11.97	32.30	11.60
Sulphate (mgSO4/L)	14.1	14.4	7.3	3.7	26.6	26.9	16.8	7.3	8.1	4.6
Temperature (°C)	4.50	5.00	5.00	4.00	5.00	6.00	5.00	2.67	4.00	4.00
Total Nitrogen (mgN/L)	0.375	0.080	0.460	0.290	0.370	0.340	0.550	0.277	0.350	0.260
Total Phosphorus (mgP/L)	0.0055	0.0000	0.0047	0.0070	0.0050	<0.002	0.0040	0.0030	0.0030	0.0077

APPENDIX 1c. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	Lamont (73)	Little Albro (78)	Long (28-30)	Loon (54, 55)	Major (50-53)	Maynards (77)	Micmac (58, 59)	Miller (46, 47)	Morris (62-64)	Oathill (75)
pH	5.02	7.01	5.72	6.55	4.28	7.25	7.41	5.95	6.93	7.17
Alkalinity (mg$CaCO_3$/L)	0.2000	9.8000	1.3667	14.3000	0.0327	16.4333	23.1500	2.3500	15.9200	24.3000
Aluminum (mg/L)	0.1020	0.0160	0.2373	0.0410	0.2300	0.0270	0.0230	0.1565	0.0524	0.0460
Ammonia (mg/L)	0.0049	0.0084	0.0160	0.0113	0.0101	0.0114	0.0051	0.1119	0.0132	0.0233
Calcium (mg/L)	2.20	10.60	6.17	9.85	0.95	10.93	24.25	3.70	12.90	19.00
Chloride (mg/L)	16.6	118.6	77.7	79.1	6.8	88.2	235.7	26.2	103.2	158.6
Chlorophyll (µg/L)	1.2	1.1	0.7	1.1	0.4	0.8	0.5	1.1	0.9	2.1
Colour (TCU)	10.3	7.4	51.8	12.4	33.6	9.0	9.5	38.5	13.8	15.7
Conductivity (µS/cm)	80.40	476.00	304.50	337.50	40.35	379.33	917.00	122.50	432.67	656.00
Diss. Organic Carbon (mg/L)	2.70	2.20	6.53	3.35	5.03	2.60	3.20	5.20	3.00	3.10
Magnesium (mg/L)	0.90	1.10	1.13	1.55	0.50	1.67	2.50	0.70	1.70	2.70
Nitrate (mgN/L)	0.0371	0.0599	0.0831	0.1998	0.0381	0.0854	0.2808	0.2779	0.2089	0.7144
Phosphate (mgP/L)	<0.001	0.00098	<0.001	0.00242	<0.001	0.00085	0.00275	<0.001	0.00141	0.00343
Potassium (mg/L)	0.60	0.90	0.80	1.30	0.50	1.20	1.75	0.80	1.36	1.80
Silica (mgSi/L)	0.0241	0.1923	0.0658	0.4528	0.1562	0.4159	0.4976	0.0674	0.4177	0.8393
Sodium (mg/L)	9.60	73.50	44.57	48.50	4.13	55.23	139.00	16.05	61.56	96.50
Sulphate (mgSO_4/L)	5.9	11.6	9.0	10.1	3.2	11.1	22.1	6.2	12.5	17.9
Temperature (°C)	5.00	6.50	4.00	4.50	3.50	5.50	5.50	4.00	4.00	5.70
Total Nitrogen (mgN/L)	0.130	0.180	0.280	0.380	0.158	0.247	0.400	0.560	0.366	0.890
Total Phosphorus (mgP/L)	<0.002	0.0040	0.0047	0.0045	0.0033	0.0043	0.0035	0.0065	0.0058	0.0100

APPENDIX 1d. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	Paper Mill (16)	Parr (33)	Penhorn (76)	Powder Mill (11)	Power Pond (86)	Rocky (12, 13)	Russell (65, 66)	Sandy (14, 15)	Second (9-10)
pH	6.37	6.36	7.20	6.51	5.68	7.20	7.02	6.12	4.71
Alkalinity ($mgCaCO_3/L$)	2.6000	4.6000	25.1000	17.6000	1.0000	22.4500	25.4500	3.6500	9.1000
Aluminum (mg/L)	0.1750	0.2120	0.0340	0.0240	0.2470	0.0285	0.0915	0.1510	0.0880
Ammonia (mg/L)	0.0090	0.0036	0.0047	0.0060	0.0034	0.0054	0.0081	0.0124	0.0049
Calcium (mg/L)	6.50	4.90	18.80	11.30	4.40	15.75	23.00	5.95	6.30
Chloride (mg/L)	61.5	16.7	159.1	47.8	49.8	75.3	233.6	53.6	36.4
Chlorophyll (µg/L)	0.4	1.0	3.5	4.4	1.6	10.8	11.7	1.5	0.7
Colour (TCU)	26.6	68.5	11.0	14.4	48.8	16.3	19.0	28.2	24.3
Conductivity (µS/cm)	252.00	94.20	654.00	239.00	208.00	345.50	899.50	224.50	165.00
Diss. Organic Carbon (mg/L)	3.70	7.50	2.50	3.30	6.20	3.05	3.00	4.15	4.50
Magnesium (mg/L)	1.20	0.80	1.70	1.20	1.00	1.50	2.35	1.15	1.05
Nitrate (mgN/L)	0.2226	0.0646	0.0403	0.2132	0.0770	0.2029	0.0071	0.1612	0.0503
Phosphate (mgP/L)	<0.001	<0.001	0.00284	<0.001	0.00105	0.00427	0.00408	<0.001	0.00193
Potassium (mg/L)	0.90	0.80	2.00	1.90	0.90	2.40	2.00	1.10	0.95
Silica (mgSi/L)	0.1734	0.1411	0.1698	0.5874	0.0764	0.2636	0.3917	0.1844	0.4978
Sodium (mg/L)	36.40	10.00	93.80	27.30	28.30	43.45	138.60	31.20	21.50
Sulphate ($mgSO_4/L$)	8.4	7.3	14.6	9.6	7.3	13.1	20.3	7.7	5.2
Temperature (°C)	5.00	5.00	6.00	4.00	5.00	5.00	5.50	4.50	4.00
Total Nitrogen (mgN/L)	0.350	0.260	0.210	0.400	0.260	0.380	0.175	0.310	0.220
Total Phosphorus (mgP/L)	0.0020	0.0100	0.0060	0.0040	0.0080	0.0080	0.0050	0.0060	0.0040

APPENDIX 1e. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	Second Chain (26)	Settle (81)	Soldier (43-45)	Spider (48, 49)	Spruce Hill (34)	Susie (19, 20)	Third (7, 8)	Thomas (38, 39)	Topsail (74)
pH	6.40	7.10	5.67	4.69	4.56	4.71	6.56	6.67	5.26
Alkalinity ($mgCaCO_3/L$)	-0.7000	23.3000	1.8000	-0.1000	-0.6000	-0.2000	10.3000	9.4500	0.8000
Aluminum (mg/L)	0.6880	0.1530	0.1893	0.1715	0.2520	0.3300	0.0285	0.0665	0.0790
Ammonia (mg/L)	0.0389	0.0068	0.1906	0.0090	0.0037	0.0056	0.0045	0.0229	0.0044
Calcium (mg/L)	6.90	16.30	3.10	0.95	0.50	5.80	6.25	6.80	2.50
Chloride (mg/L)	118.8	137.5	21.2	6.0	7.2	70.0	28.1	36.3	18.2
Chlorophyll (µg/L)	0.9	16.3	0.6	1.0	1.4	1.1	2.7	1.1	1.1
Colour (TCU)	5.2	31.8	46.7	34.6	47.6	32.6	16.1	23.2	8.6
Conductivity (µS/cm)	466.00	563.00	104.67	35.40	39.90	285.00	141.50	172.50	86.30
Diss. Organic Carbon (mg/L)	1.20	3.90	6.23	4.80	6.10	4.55	3.65	3.95	2.20
Magnesium (mg/L)	1.30	2.30	0.60	0.50	0.50	1.00	1.00	0.90	0.80
Nitrate (mgN/L)	0.0431	0.1625	0.3354	0.0170	0.0209	0.0692	0.1175	0.2077	0.0431
Phosphate (mgP/L)	<0.001	0.00550	<0.001	<0.001	<0.001	<0.001	0.00091	<0.001	<0.001
Potassium (mg/L)	0.90	1.60	0.80	0.50	0.50	0.60	1.00	1.15	0.60
Silica (mgSi/L)	0.6334	0.1915	0.0482	0.1089	0.2007	0.5349	0.4298	0.5390	0.0252
Sodium (mg/L)	67.90	83.20	13.27	3.40	4.20	39.30	16.20	21.25	10.90
Sulphate ($mgSO_4/L$)	16.2	13.3	6.2	2.7	1.9	10.1	5.4	7.2	6.1
Temperature (°C)	5.00	4.90	3.00	4.50	4.00	4.50	4.00	4.00	5.00
Total Nitrogen (mgN/L)	0.130	0.460	0.710	0.135	0.150	0.185	0.270	0.400	0.120
Total Phosphorus (mgP/L)	<0.002	0.0170	0.0053	0.0020	0.0020	0.0050	0.0035	0.0045	<0.002

APPENDIX 1f. pH, major ions, nutrients and organic matter data for 2011.

Lake Name (Station #)	Whimsical (84)	William (40-42)	Williams (31)
pH	6.57	6.84	6.28
Alkalinity ($mgCaCO_3/L$)	18.1000	11.2000	2.6000
Aluminum (mg/L)	0.0820	0.0483	0.1680
Ammonia (mg/L)	0.8533	0.0064	0.0071
Calcium (mg/L)	26.50	7.63	6.00
Chloride (mg/L)	263.8	38.8	54.2
Chlorophyll (µg/L)	1.7	1.2	1.2
Colour (TCU)	10.6	19.7	21.3
Conductivity (µS/cm)	1060.00	185.67	234.00
Diss. Organic Carbon (mg/L)	2.20	3.70	3.80
Magnesium (mg/L)	3.00	1.03	1.10
Nitrate (mgN/L)	0.4096	0.1945	0.1869
Phosphate (mgP/L)	0.00319	<0.001	<0.001
Potassium (mg/L)	2.50	1.30	1.00
Silica (mgSi/L)	0.4597	0.8648	0.1210
Sodium (mg/L)	159.40	23.10	31.70
Sulphate ($mgSO_4/L$)	44.0	8.0	11.9
Temperature (°C)	7.00	3.00	5.00
Total Nitrogen (mgN/L)	1.270	0.370	0.340
Total Phosphorus (mgP/L)	0.0060	0.0043	0.0050

APPENDIX 2a. Trace element data for 2011.

Lake	Anderson (68)	Banook (69, 70)	Bayers (25)	Bell (82)	Big Albro (79)	Bissett (60, 61)	Charles (56, 57)	Chocolate (83)	Colbart (32)	Cranberry (80)
Aluminum (µg/L)	111.6	6.4	48.6	59.1	10.7	35.8	23.7	285.5	208.6	38.3
Arsenic (µg/L)	0.19	1.92	0.14	0.20	0.54	0.67	11.17	< 0.1	0.47	0.32
Cadmium (µg/L)	< 0.02	< 0.02	0.206	0.038	< 0.02	0.061	< 0.02	0.109	0.078	< 0.02
Cerium (µg/L)	0.255	0.021	0.056	0.138	0.027	0.176	0.136	1.410	0.168	0.116
Cobalt (µg/L)	0.121	< 0.05	0.543	0.103	< 0.05	0.089	0.059	3.419	0.304	0.057
Copper (µg/L)	0.50	1.19	2.30	1.41	0.97	2.80	0.90	0.88	1.27	1.24
Dysprosium (µg/L)	0.0283	< 0.005	0.0059	0.0118	< 0.005	0.0148	0.0185	0.0942	0.0276	0.0110
Erbium (µg/L)	0.0157	< 0.005	< 0.005	0.0060	< 0.005	0.0088	0.0108	0.0544	0.0166	0.0068
Europium (µg/L)	0.0090	< 0.005	< 0.005	< 0.005	< 0.005	0.0057	0.0066	0.0334	0.0060	< 0.005
Gadolinium (µg/L)	0.0376	0.0031	0.0077	0.0160	0.0052	0.0217	0.0276	0.1182	0.0298	0.0161
Holmium (µg/L)	0.0057	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.0201	0.0058	< 0.005
Indium (µg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron (µg/L)	74.0	10.8	33.0	45.0	25.0	79.5	24.0	85.0	119.0	51.0
Lanthanum (µg/L)	0.279	0.029	0.044	0.110	0.033	0.125	0.196	1.134	0.111	0.111
Lead (µg/L)	0.123	0.056	0.408	0.328	0.072	0.555	0.071	0.400	0.677	0.113
Lutetium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.0067	< 0.005	< 0.005
Manganese (µg/L)	28.84	5.07	356.16	28.58	24.49	134.70	25.69	145.25	32.49	120.98
Neodymium (µg/L)	0.2121	0.0225	0.0284	0.0917	0.0290	0.1189	0.1663	0.5708	0.1096	0.0934
Nickel (µg/L)	0.66	0.43	5.43	0.80	0.47	0.86	0.49	7.13	1.58	0.66
Praseodymium (µg/L)	0.0575	0.0054	0.0067	0.0236	0.0065	0.0286	0.0399	0.1674	0.0271	0.0240
Samarium (µg/L)	0.0367	< 0.005	0.0061	0.0196	0.0061	0.0234	0.0308	0.0913	0.0269	0.0183
Terbium (µg/L)	0.0051	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.0169	< 0.005	< 0.005
Thallium (µg/L)	< 0.005	< 0.005	0.0147	< 0.005	< 0.005	< 0.005	< 0.005	0.0154	0.0100	< 0.005
Thulium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.0071	< 0.005	< 0.005
Uranium (µg/L)	< 0.005	0.0487	0.0145	< 0.005	0.0051	0.0557	0.0830	0.0055	0.1732	0.0094
Vanadium (µg/L)	0.37	0.17	< 0.1	0.26	0.40	0.25	0.29	< 0.1	1.19	0.21
Ytterbium (µg/L)	0.013	0.007	0.005	0.007	< 0.005	0.009	0.011	0.040	0.016	0.008
Yttrium (µg/L)	0.1830	0.0325	0.0680	0.0700	0.0270	0.0880	0.1370	0.8900	0.1820	0.0850
Zinc (µg/L)	3.59	4.66	32.91	3.12	3.59	6.18	1.77	24.04	16.95	2.40

APPENDIX 2b. Trace element data for 2011.

Lake Name (Station #)	First (71 ,72)	First Chain (27)	Fletcher (35-37)	Fraser (23, 24)	Frenchman (67)	Frog Pond (85)	Governor (21, 22)	Grand (1-3)	Kearney (17, 18)	Kinsac (4-6)
Aluminum (µg/L)	15.150	478.700	77.433	199.688	15.300	35.900	190.350	64.433	186.350	111.159
Arsenic (µg/L)	0.365	0.130	1.160	0.278	0.410	0.370	0.240	0.513	0.200	0.239
Cadmium (µg/L)	< 0.02	0.083	0.015	0.083	< 0.02	< 0.02	0.137	< 0.02	0.056	0.020
Cerium (µg/L)	0.047	0.355	0.247	0.244	0.035	0.042	0.422	0.178	0.206	0.282
Cobalt (µg/L)	0.052	1.682	0.120	0.475	< 0.05	0.060	1.381	0.067	0.372	0.163
Copper (µg/L)	1.190	0.650	0.750	0.860	1.040	0.840	1.580	0.627	0.680	0.634
Dysprosium (µg/L)	0.005	0.039	0.025	0.034	0.005	0.009	0.064	0.020	0.028	0.023
Erbium (µg/L)	< 0.005	0.025	0.013	0.020	< 0.005	0.007	0.037	0.010	0.017	0.013
Europium (µg/L)	< 0.005	0.011	0.009	0.008	< 0.005	< 0.005	0.015	0.006	0.008	0.008
Gadolinium (µg/L)	0.008	0.039	0.034	0.039	0.007	0.011	0.072	0.026	0.031	0.034
Holmium (µg/L)	< 0.005	0.009	0.002	0.000	< 0.005	< 0.005	0.013	< 0.005	0.006	0.002
Indium (µg/L)	< 0.01	< 0.01	< 0.01	0.000	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron (µg/L)	21.500	69.000	89.333	140.375	35.000	39.000	114.500	58.000	89.000	105.556
Lanthanum (µg/L)	0.034	0.331	0.202	0.144	0.061	0.039	0.272	0.137	0.150	0.173
Lead (µg/L)	0.054	0.519	0.145	0.433	0.124	0.090	0.387	0.124	0.308	0.177
Lutetium (µg/L)	< 0.005	< 0.005	< 0.005	0.000	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Manganese (µg/L)	46.240	103.400	34.993	65.851	9.090	7.200	153.305	16.223	48.335	44.314
Neodymium (µg/L)	0.032	0.180	0.183	0.155	0.035	0.038	0.267	0.132	0.128	0.173
Nickel (µg/L)	0.565	3.020	0.710	1.488	0.700	2.410	4.390	0.643	1.940	0.689
Praseodymium (µg/L)	0.008	0.049	0.046	0.036	0.009	0.008	0.063	0.033	0.032	0.044
Samarium (µg/L)	0.007	0.030	0.035	0.035	0.006	0.008	0.061	0.027	0.028	0.036
Terbium (µg/L)	< 0.005	0.007	0.002	0.000	< 0.005	< 0.005	0.011	< 0.005	< 0.005	0.002
Thallium (µg/L)	< 0.005	0.014	< 0.005	0.006	< 0.005	0.006	0.009	< 0.005	0.007	< 0.005
Thulium (µg/L)	< 0.005	< 0.005	< 0.005	0.000	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Uranium (µg/L)	0.034	0.016	0.038	0.141	0.011	0.040	0.277	0.023	0.086	0.022
Vanadium (µg/L)	< 0.1	< 0.1	0.163	0.361	0.780	0.350	0.185	< 0.1	0.385	0.138
Ytterbium (µg/L)	< 0.005	0.018	0.012	0.017	< 0.005	0.008	0.031	0.009	0.014	0.012
Yttrium (µg/L)	0.037	0.361	0.146	0.225	0.043	0.058	0.475	0.111	0.198	0.135
Zinc (µg/L)	2.155	15.740	2.790	11.886	4.980	9.490	29.215	2.313	10.525	4.288

APPENDIX 2c. Trace element data for 2011.

Lake	Lamont (73)	Little Albro (78)	Long (28-30)	Loon (54, 55)	Major (50-53)	Maynards (77)	Micmac (58, 59)	Miller (46, 47)	Morris (62-64)	Oathill (75)
Aluminum (µg/L)	88.0	9.5	212.8	31.8	218.1	16.8	10.3	138.1	23.9	25.7
Arsenic (µg/L)	0.24	0.70	0.25	0.41	0.51	0.36	2.22	0.22	0.33	0.55
Cadmium (µg/L)	0.046	< 0.02	0.045	< 0.02	0.035	< 0.02	< 0.02	0.023	< 0.02	< 0.02
Cerium (µg/L)	0.153	0.048	0.250	0.113	0.345	0.073	0.044	0.366	0.089	0.106
Cobalt (µg/L)	0.248	< 0.05	0.262	0.089	0.238	0.067	0.069	0.129	0.059	0.092
Copper (µg/L)	1.00	1.09	0.83	1.17	0.41	1.15	1.11	0.80	1.23	1.85
Dysprosium (µg/L)	0.0122	0.0056	0.0294	0.0098	0.0257	0.0068	0.0080	0.0268	0.0095	0.0128
Erbium (µg/L)	0.0075	< 0.005	0.0168	0.0063	0.0144	< 0.005	0.0075	0.0143	0.0060	0.0091
Europium (µg/L)	< 0.005	< 0.005	0.0071	< 0.005	0.0081	< 0.005	< 0.005	0.0092	< 0.005	0.0054
Gadolinium (µg/L)	0.0163	0.0071	0.0347	0.0147	0.0350	0.0090	0.0083	0.0382	0.0133	0.0207
Holmium (µg/L)	< 0.005	< 0.005	0.0061	< 0.005	< 0.005	< 0.005	< 0.005	0.0052	0.0000	< 0.005
Indium (µg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron (µg/L)	31.0	33.0	234.3	69.0	105.8	69.7	15.5	136.5	35.7	65.0
Lanthanum (µg/L)	0.153	0.040	0.155	0.097	0.259	0.059	0.054	0.222	0.085	0.120
Lead (µg/L)	0.315	0.115	0.413	0.236	0.293	0.177	0.056	0.185	0.055	0.209
Lutetium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Manganese (µg/L)	91.85	20.89	50.20	97.89	98.91	69.56	24.89	42.76	69.42	87.50
Neodymium (µg/L)	0.1110	0.0380	0.1469	0.0813	0.1969	0.0479	0.0438	0.2111	0.0714	0.1045
Nickel (µg/L)	1.20	0.47	1.12	0.65	0.67	0.96	0.43	0.77	0.70	0.71
Praseodymium (µg/L)	0.0291	0.0091	0.0359	0.0199	0.0520	0.0118	0.0105	0.0516	0.0177	0.0253
Samarium (µg/L)	0.0171	0.0067	0.0318	0.0146	0.0369	0.0090	0.0083	0.0392	0.0130	0.0201
Terbium (µg/L)	< 0.005	< 0.005	0.0053	< 0.005	< 0.005	< 0.005	< 0.005	0.0054	< 0.005	< 0.005
Thallium (µg/L)	< 0.005	< 0.005	0.0065	< 0.005	0.0080	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Thulium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Uranium (µg/L)	< 0.005	0.0058	0.0941	0.0065	0.0736	0.0057	0.0738	0.0513	0.0229	0.0180
Vanadium (µg/L)	0.29	0.28	0.45	0.17	0.59	0.33	0.24	0.24	0.20	0.87
Ytterbium (µg/L)	0.007	< 0.005	0.015	0.006	0.013	< 0.005	0.009	0.013	0.007	0.009
Yttrium (µg/L)	0.0990	0.0270	0.1940	0.0600	0.1686	0.0417	0.0555	0.1545	0.0636	0.0920
Zinc (µg/L)	6.28	5.41	8.17	2.82	4.07	5.43	6.23	2.80	5.23	9.54

APPENDIX 2d. Trace element data for 2011.

Lake	Paper Mill (16)	Parr (33)	Penhorn (76)	Powder Mill (11)	Power Pond (86)	Rocky (12, 13)	Russell (65, 66)	Sandy (14, 15)	Second (9-10)
Aluminum (µg/L)	158.9	192.6	12.1	16.3	222.7	16.6	27.5	120.6	46.5
Arsenic (µg/L)	0.15	0.31	0.36	1.20	0.42	0.53	0.31	0.26	0.26
Cadmium (µg/L)	0.050	0.034	< 0.02	< 0.02	0.039	< 0.02	< 0.02	0.041	< 0.02
Cerium (µg/L)	0.196	0.174	0.034	0.052	0.240	0.065	0.142	0.348	0.099
Cobalt (µg/L)	0.225	0.057	< 0.05	0.060	0.165	0.084	0.143	0.374	< 0.05
Copper (µg/L)	0.66	0.69	0.98	0.73	0.88	0.71	1.44	0.82	0.56
Dysprosium (µg/L)	0.0237	0.0212	0.0058	0.0084	0.0315	0.0081	0.0128	0.0287	0.0135
Erbium (µg/L)	0.0144	0.0115	< 0.005	0.0057	0.0157	< 0.005	0.0079	0.0155	0.0064
Europium (µg/L)	0.0074	< 0.005	< 0.005	< 0.005	0.0058	< 0.005	0.0062	0.0098	0.0027
Gadolinium (µg/L)	0.0288	0.0247	0.0051	0.0107	0.0329	0.0116	0.0169	0.0392	0.0177
Holmium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	0.0054	< 0.005	< 0.005	0.0057	< 0.005
Indium (µg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron (µg/L)	82.0	143.0	12.0	29.0	154.0	30.0	77.0	184.0	57.0
Lanthanum (µg/L)	0.152	0.102	0.028	0.054	0.133	0.062	0.120	0.215	0.072
Lead (µg/L)	0.287	0.496	0.032	0.051	0.537	0.073	0.144	0.270	0.082
Lutetium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Manganese (µg/L)	41.57	5.93	87.07	10.07	31.22	10.61	326.52	95.73	6.05
Neodymium (µg/L)	0.1287	0.1066	0.0267	0.0492	0.1386	0.0582	0.0904	0.2067	0.0814
Nickel (µg/L)	1.74	0.46	0.45	0.40	0.87	0.34	0.77	1.18	0.34
Praseodymium (µg/L)	0.0324	0.0266	0.0062	0.0115	0.0321	0.0133	0.0245	0.0520	0.0189
Samarium (µg/L)	0.0283	0.0244	0.0055	0.0119	0.0333	0.0121	0.0193	0.0416	0.0161
Terbium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.0053	< 0.005
Thallium (µg/L)	0.0053	0.0056	< 0.005	< 0.005	0.0090	< 0.005	< 0.005	< 0.005	< 0.005
Thulium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Uranium (µg/L)	0.0600	0.0834	0.0237	0.0472	0.1501	0.0982	0.0487	0.0129	0.0121
Vanadium (µg/L)	0.30	0.74	0.17	0.10	0.77	0.12	0.27	0.23	0.13
Ytterbium (µg/L)	0.014	0.010	0.006	0.005	0.015	0.006	0.009	0.014	0.006
Yttrium (µg/L)	0.1810	0.1280	0.0320	0.0510	0.1750	0.0515	0.0830	0.1685	0.0685
Zinc (µg/L)	8.84	5.45	3.49	1.71	8.25	0.95	7.92	6.32	1.27

APPENDIX 2e. Trace element data for 2011.

Lake	Second Chain (26)	Settle (81)	Soldier (43-45)	Spider (48, 49)	Spruce Hill (34)	Susie (19, 20)	Third (7, 8)	Thomas (38, 39)	Topsail (74)	Whimsical (84)
Aluminum (µg/L)	719.3	68.5	173.3	164.1	251.6	317.4	18.4	54.6	58.6	32.2
Arsenic (µg/L)	0.12	0.54	0.20	0.14	0.36	0.18	0.30	1.78	0.25	0.28
Cadmium (µg/L)	0.129	< 0.02	< 0.02	0.035	0.040	0.092	< 0.02	< 0.02	0.038	0.080
Cerium (µg/L)	0.392	0.238	0.440	0.473	0.228	0.385	0.044	0.184	0.125	0.158
Cobalt (µg/L)	2.254	0.153	0.213	0.264	0.160	1.527	< 0.05	0.077	0.210	3.061
Copper (µg/L)	0.86	1.76	0.72	0.51	0.42	0.82	0.85	0.69	0.56	1.51
Dysprosium (µg/L)	0.0469	0.0195	0.0298	0.0313	0.0211	0.0453	0.0084	0.0205	0.0110	0.0141
Erbium (µg/L)	0.0271	0.0106	0.0152	0.0176	0.0123	0.0276	0.0055	0.0108	0.0070	0.0097
Europium (µg/L)	0.0110	0.0075	0.0096	0.0094	< 0.005	0.0128	< 0.005	0.0066	< 0.005	0.0063
Gadolinium (µg/L)	0.0430	0.0256	0.0399	0.0421	0.0270	0.0490	0.0129	0.0272	0.0150	0.0181
Holmium (µg/L)	0.0097	< 0.005	0.0056	0.0062	< 0.005	0.0096	< 0.005	< 0.005	< 0.005	< 0.005
Indium (µg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron (µg/L)	79.0	166.0	171.0	137.5	229.0	108.5	21.0	60.5	25.0	42.0
Lanthanum (µg/L)	0.382	0.178	0.223	0.391	0.108	0.261	0.050	0.178	0.150	0.134
Lead (µg/L)	0.738	0.246	0.228	0.259	0.648	0.592	0.068	0.106	0.166	0.082
Lutetium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Manganese (µg/L)	122.08	286.86	52.16	73.51	32.89	121.25	2.29	27.30	71.27	451.41
Neodymium (µg/L)	0.1839	0.1668	0.2121	0.2691	0.1147	0.1898	0.0523	0.1566	0.0995	0.0842
Nickel (µg/L)	4.01	0.69	0.82	0.98	0.37	4.62	0.42	0.52	0.88	15.78
Praseodymium (µg/L)	0.0510	0.0404	0.0540	0.0729	0.0276	0.0480	0.0123	0.0376	0.0269	0.0228
Samarium (µg/L)	0.0351	0.0292	0.0419	0.0449	0.0262	0.0413	0.0129	0.0287	0.0161	0.0169
Terbium (µg/L)	0.0078	< 0.005	0.0054	0.0054	< 0.005	0.0077	< 0.005	< 0.005	< 0.005	< 0.005
Thallium (µg/L)	0.0182	< 0.005	0.0017	0.0026	0.0085	0.0113	< 0.005	< 0.005	< 0.005	0.0128
Thulium (µg/L)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Uranium (µg/L)	0.0289	0.0228	0.0611	0.0028	0.0331	0.0690	0.0124	0.0288	< 0.005	0.0705
Vanadium (µg/L)	< 0.1	0.46	0.31	0.52	0.42	0.52	< 0.1	0.17	0.20	0.15
Ytterbium (µg/L)	0.021	0.010	0.013	0.016	0.010	0.022	< 0.005	0.009	0.006	0.011
Yttrium (µg/L)	0.4200	0.1040	0.1600	0.2075	0.1260	0.3500	0.0495	0.1225	0.0850	0.1110
Zinc (µg/L)	21.29	6.92	3.37	4.69	4.08	18.08	1.52	2.40	5.39	53.04

APPENDIX 2f. Trace element data for 2011.

Lake	William (40-42)	Williams (31)
Aluminum (µg/L)	38.5	144.9
Arsenic (µg/L)	1.98	0.37
Cadmium (µg/L)	< 0.02	0.067
Cerium (µg/L)	0.147	0.132
Cobalt (µg/L)	0.060	0.380
Copper (µg/L)	0.71	1.12
Dysprosium (µg/L)	0.0182	0.0215
Erbium (µg/L)	0.0103	0.0133
Europium (µg/L)	0.0060	0.0060
Gadolinium (µg/L)	0.0251	0.0254
Holmium (µg/L)	< 0.005	0.0050
Indium (µg/L)	< 0.01	< 0.01
Iron (µg/L)	35.0	75.0
Lanthanum (µg/L)	0.188	0.114
Lead (µg/L)	0.067	0.436
Lutetium (µg/L)	< 0.005	< 0.005
Manganese (µg/L)	14.44	26.33
Neodymium (µg/L)	0.1516	0.0921
Nickel (µg/L)	0.44	2.65
Praseodymium (µg/L)	0.0385	0.0229
Samarium (µg/L)	0.0263	0.0217
Terbium (µg/L)	< 0.005	< 0.005
Thallium (µg/L)	< 0.005	0.0068
Thulium (µg/L)	< 0.005	< 0.005
Uranium (µg/L)	0.0268	0.0904
Vanadium (µg/L)	0.17	0.58
Ytterbium (µg/L)	0.009	0.012
Yttrium (µg/L)	0.1230	0.1590
Zinc (µg/L)	2.34	18.52

APPENDIX 3. Sampling station positions.

Station #	Lake	Latitude	Longitude
1	Grand Lake	44.93661	-63.5831
2	Grand Lake	44.91158	-63.6012
3	Grand Lake	44.88474	-63.6184
4	Kinsac Lake	44.84611	-63.6542
5	Kinsac Lake	44.82681	-63.6542
6	Kinsac Lake	44.81434	-63.6469
7	Third Lake	44.79825	-63.6385
8	Third Lake	44.78999	-63.6333
9	Second Lake	44.78314	-63.6432
10	Second Lake	44.78289	-63.6605
11	Powder Mill Lake	44.77398	-63.6094
12	Rocky Lake	44.76563	-63.6199
13	Rocky Lake	44.75923	-63.6329
14	Sandy Lake	44.73548	-63.7
15	Sandy Lake	44.73034	-63.7016
16	Paper Mill Lake	44.71622	-63.6888
17	Kearney Lake	44.69876	-63.7052
18	Kearney Lake	44.69305	-63.6922
19	Susie Lake	44.67263	-63.6912
20	Susie Lake	44.65969	-63.699
21	Governor Lake	44.64114	-63.697
22	Governor Lake	44.64523	-63.7065
23	Fraser Lake	44.67073	-63.7557
24	Fraser Lake	44.68125	-63.7698
25	Bayers Lake	44.64272	-63.6707
26	Second Chain Lake	44.63616	-63.6532
27	First Chain Lake	44.63883	-63.6436
28	Long Lake	44.62635	-63.6514
29	Long Lake	44.62151	-63.637

Station #	Lake	Latitude	Longitude
30	Long Lake	44.61655	-63.6255
31	Williams Lake	44.62055	-63.592
32	Colbart lake	44.6096	-63.5967
33	Parr Lake	44.56499	-63.6056
34	Spruce Hill Lake	44.58004	-63.6509
35	Lake Fletcher	44.85314	-63.6141
36	Lake Fletcher	44.84373	-63.6107
37	Lake Fletcher	44.83484	-63.6126
38	Lake Thomas	44.81019	-63.6108
39	Lake Thomas	44.79515	-63.6097
40	Lake William	44.77656	-63.5937
41	Lake William	44.7688	-63.5862
42	Lake William	44.75925	-63.5767
43	Soldier Lake	44.82616	-63.5728
44	Soldier Lake	44.81657	-63.5706
45	Soldier Lake	44.80732	-63.5711
46	Miller Lake	44.82334	-63.5929
47	Miller Lake	44.81209	-63.5933
48	Spider Lake	44.75324	-63.5435
49	Spider Lake	44.75707	-63.539
50	Lake Major	44.76264	-63.5105
51	Lake Major	44.74577	-63.4988
52	Lake Major	44.73441	-63.4903
53	Lake Major	44.72585	-63.4792
54	Loon Lake	44.70623	-63.5099
55	Loon Lake	44.7008	-63.5036
56	Lake Charles	44.73224	-63.5526
57	Lake Charles	44.7149	-63.5485
58	Lake Micmac	44.69498	-63.5557
59	Lake Micmac	44.68879	-63.5497
60	Bissett Lake	44.66088	-63.4727
61	Bissett Lake	44.65192	-63.4681

Station #	Lake	Latitude	Longitude
62	Morris Lake	44.6437	-63.4913
63	Morris Lake	44.65656	-63.5049
64	Morris Lake	44.66135	-63.51
65	Russell Lake	44.66673	-63.5261
66	Russell Lake	44.66183	-63.5227
67	Frenchman Lake	44.69903	-63.5763
68	Anderson Lake	44.72687	-63.6199
69	Lake Banook	44.68222	-63.5535
70	Lake Banook	44.67826	-63.5591
71	First Lake	44.77425	-63.6695
72	First Lake	44.76647	-63.6569
73	Lamont Lake	44.69034	-63.5218
74	Topsail Lake	44.69429	-63.517
75	Oakhill Lake	44.67415	-63.5502
76	Penhorn Lake	44.67562	-63.5407
77	Maynards Lake	44.67076	-63.5523
78	Little Albro Lake	44.6844	-63.5769
79	Big Albro Lake	44.6892	-63.5773
80	Cranberry Lake	44.6895	-63.4979
81	Settle Lake	44.67928	-63.5046
82	Bell Lake	44.67511	-63.5096
83	Chocolate Lake	44.63884	-63.6225
84	Whimsical Lake	44.62571	-63.6094
85	Frog Pond	44.62683	-63.6029
86	Power Pond	44.57672	-63.555