

Aquatic Ecology & Water Quality Management Group, Wageningen University

Environmental Management of Drinking Water Group, University of Victoria

Report of a co-op period in Canada

Paleolimnological study of Elk Lake

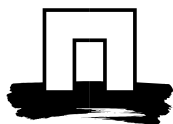
150 – 500 Years of inferred water quality developments

Roel Groeneveld

20 December 2002

Registration number: 78-01-08-281-030

Environmental sciences



WAGENINGEN UNIVERSITY
ENVIRONMENTAL SCIENCES



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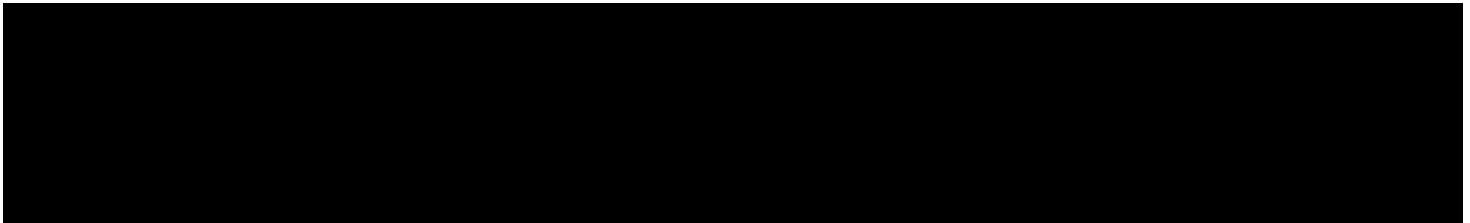
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Abstract

Elk Lake is a relatively small (246 ha) and shallow (>18m) lake situated on Vancouver Island (BC, Canada). It turned into a eutrophic system over the last 50 years, most likely due to anthropogenic disturbances of its watershed. Because the state of the ecosystem before settlement of the area is not known, the present situation cannot be compared to the original condition of the lake. This hampers present day water quality management because there is no reference value against which current ecological information and scenarios for the lake's future can be compared.

Paleolimnological methods and techniques can enable researchers to retrieve historic data from sediment cores. This approach can be very useful for identifying the important developments in the state of the water quality of the Elk Lake ecosystem over the past 150 years, and for linking these to historic records on natural and anthropogenic disturbances that occurred in the watershed.

In this project, the sediment cores were retrieved from the lake using a modified gravity corer. ^{210}Pb -dating of sediment subsamples was done using alpha spectrometry. Concentrations of nutrients, heavy metals and other elements were determined, and for each subsample the relative abundance of the present diatom species (or genera) was assessed as well. Furthermore, water quality data on Elk Lake for the past decades was retrieved from government databases.

Readily visible are the doubling and tripling of heavy metal concentrations in the lakes sediment between the first and second half of the 19th century. Sediment accumulation rates show a sharp increase from 1950 onward. The stable C:N ratio indicates that sources of organic matter present in the water column hardly changed over the past 400 years.

Of the present diatoms, *Aulacoseira* was the most dominant genus over the past centuries. During the last decades, eutrophic genera like *Stephanodiscus* became increasingly abundant. This is in line with public observations that the water quality of Elk Lake has been deteriorating since the mid 1980s.

The integration of the results of all analyses made it possible to identify three important events or developments affecting the lake's condition: the 16th century megadrought; the settlement of the Greater Victoria area, and the intensified land use after World War II. Against expectations, the construction of both the Victoria Waterworks and the Patricia Bay Highway were not extractable from the results.

Advanced statistical analyses may be necessary to retrieve more information from the collected data set. In that aspect, the diatom data should be verified before this set of data is reused in other (follow-up) projects. After verification, this subset can be used for detailed inferences of water quality developments in Elk Lake.

Table of Contents

Abstract	1
Table of Contents	4
Acknowledgments	6
1 Introduction	7
1.1 General introduction	7
1.2 Use of paleolimnological approaches	7
1.3 Hypothesis	8
1.4 Research question	9
1.5 Objectives	10
2 The Elk Lake watershed: past & present	11
2.1 Location	11
2.2 History of the Elk Lake watershed	11
2.2.1 Historic usage of the water from Elk & Beaver Lake	11
2.2.2 Hydrological changes in and around Elk Lake	12
2.3 Lake characteristics	12
2.4 Water quality management	13
2.4.1 Recent water quality monitoring of Elk Lake	13
2.4.2 Designated uses & objectives	14
3 Paleolimnological techniques and approaches	16
3.1 Introduction	16
3.2 The Sedimentary Record	17
3.2.1 Deposition and accumulation of sediments	17
3.2.2 Composition of the sedimentary record	17
3.3 Biological indicators	18
3.3.1 Diatoms	18
3.3.2 Chironomids	19
3.3.3 Other biological proxies	19
3.4 Geochemical characteristics	20
3.5 210-Pb sediment dating	21
3.6 Recent Paleolimnological Projects	22
4 Materials & methods for sediment and diatom analysis	23
4.1 Introduction	23
4.2 Sediment core	23
4.2.1 Coring procedure	23
4.2.2 210-Pb Dating of the sediment core sections	23
4.2.3 Geochemical analysis of the sediment	24
4.3 Diatom Analysis	24
4.3.1 Diatom preparation	24
4.3.2 Diatom Identification and Counts	25
4.4 Water quality data	25
5 Results of paleolimnological research	26
5.1 Introduction	26
5.2 Sediment core	26
5.2.1 Visual inspection of the sediment	26

5.2.2	210-Pb dating of the core	27
5.2.3	Sediment accumulation rate	28
5.2.4	Geochemistry	29
5.3	Diatom species composition and stratigraphy	32
5.4	Water quality developments	34
5.4.1	Two decades of Elk Lake sampling	34
6	Discussion	36
6.1	Inferred water quality trends from a 210-Pb dated sediment core	36
6.1.1	Interpretation of sediment data	36
6.1.2	Diatom identification & counts	36
6.2	Measured vs. inferred water quality data	37
6.2.1	Comparison of data with other projects	37
6.2.2	Representability of the data	37
6.3	Connecting historical information with (inferred) data	37
7	Conclusions & recommendations for Elk Lake	38
7.1	Large developments affecting Elk Lake's water quality	38
7.2	Inference of detailed water quality trends	39
7.3	Recommendations for future Elk Lake research	39
	References	40
	Appendix A: Historic events in Elk Lake watershed	43
	Appendix B: Bathymetric map of Elk & Beaver Lakes	45
	Appendix C: Elk Lake Diatoms	46
	Appendix D: Uses of modified Telmer gravity corer	48

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1 Introduction

1.1 General introduction

Eutrophication of Elk and Beaver Lake¹ (hereafter referred to as Elk Lake) is seen as a serious problem by those responsible for the water quality of this aquatic system. During the summer months, the lake system is dominated by cyanophytes and there is a strong oxygen depletion in the hypolimnion. This is an undesirable condition, considering Elk Lake is one of the most popular freshwater recreation and fisheries areas on Vancouver Island (British Columbia, Canada), with approximately 250,000 recreational visits per year (McKean, 1992).

Since the 1950's, some water quality parameters of the Elk Lake system have been measured on an irregular basis during fisheries surveys and other studies. However, there was still relatively little information available on the biological and chemical condition of the lake before the start of monitoring by the Ministry of Environment in the late 1970's. During the 80's and 90's, the lakes were sampled on a regular basis.

The lack of data on Elk Lake's water quality background and development before this time hampers the use of predictive management tools (which require a certain amount of knowledge about the development of the lake in the past) thus making it difficult to predict how the lake will change in the future. For example, at the moment there is no information available that enables water quality managers to establish if Elk Lake was a naturally productive or oligotrophic system before large groups of settlers arrived in the watershed area in the 19th century. If the system was in fact eutrophic before that time, efforts aimed at reduction of nutrient levels may very well have little or no effect in the present situation.

A complete set of historical water quality data can help water quality managers to compose realistic and feasible objectives. Using paleolimnological techniques, the historical conditions of an aquatic ecosystem can be inferred from information contained in lake sediments. Thus, these sediment records provide a useful archive of the past changes of biological, chemical and physical indicators of environmental change.

1.2 Use of paleolimnological approaches

Paleolimnological approaches can be used to research how local watersheds have responded to human impacts in the recent past, or to identify patterns of global climate change over longer periods (Wetzel, 1983). These techniques offer a solution to the problem of inadequate historical data on lakes (Smol, 1992). They can provide a long-term record of the history of the ecosystem, against which the impact of forest harvesting, human colonisation and natural extremes like forest fires on the water quality of the overlying water layer can be assessed.

¹ Beaver Lake should be considered an arm of Elk Lake, as it possesses no distinctive characteristics which set it apart from Elk Lake (Nordin, 1981).

Gorham *et al.* (2001) found that, in general, paleoecological² studies can answer five questions:

1. What were the properties of communities, ecosystems, and landscapes prior to or following natural and human disturbances?
2. What has been the pattern of recovery from disturbance, and was the prior state re-established?
3. What is the nature and magnitude of natural variability, and the frequency of extreme conditions?
4. Were communities and ecosystems relatively stable prior to disturbance, or were there significant trends or fluctuations in some of their properties?
5. Do anthropogenic disturbances have effects that are different in degree or kind from those of natural disturbances?

The above can be seen as the more generalized versions of the questions this research project will try to answer for Elk Lake.

The paleolimnological approach can provide scientists and lake managers with an (inferred) approximation of the water quality situation at a certain time or time interval in the past, and how the ecosystem developed after that period. Using this information, sudden changes in inferred water quality can be linked to known events that have probably affected the aquatic ecosystem, for instance natural extremes and certain anthropogenic activities. With this knowledge, lake management can be adapted and customized to prevent (significant) worsening of the water quality and the causes of them. Long-term planning can be built upon knowledge of past developments.

1.3 Hypothesis

Over the last century, the status of Elk Lake changed rapidly from rural lake to drinking water source and finally to recreational lake located in an urban area. It is expected that the input (both quantitative and qualitative) of allochthonous materials, water and nutrients into the lake system changed as a consequence of these developments, and hence the trophic state of the aquatic ecosystem. Natural extremes may have had an equally great impact on the lake, just as Laird *et al.* (2001) concluded for lakes on the west coast of Vancouver Island, but the effect of the urban setting is probably the most important factor influencing the ecosystem (Greenaway, 1997).

There have been both one-time events and long-term developments that presumably had an impact on the Elk Lake watershed. Important events were the:

- Permanent settling of the watershed by European colonists around the 2nd half of the 19th century;
- Creation of the Victoria waterworks at the end of that century; and
- Construction of the Patricia Bay Highway running along the east side of the lake in the mid of the 20th century.

Both altered the hydrology of the lake by controlling the lake level and volume and modifying the drainage and runoff of precipitation into the water body. During

² Paleoecology: taken here to include the disciplines of paleolimnology, paleo geochemistry, and paleoclimatology (Gorham *et al.*, 2001).

construction, erosion of soil and runoff of construction materials might have (slightly) changed the composition of the lake.

On a larger time scale, the drainage area of the lake has been influenced by:

- Deforestation, to clear land for other uses like agriculture;
- Urbanization, due to the growth of the population in the Greater Victoria area; and
- Increasing use of the lakes as recreational areas.

The deforestation and other land-uses may have resulted in increased erosion of mineral soils and nutrient inputs. These developments probably enhanced sedimentation and aquatic productivity, thereby changing the amount of organic material, the accumulation of carbon and nitrogen, and the C:N ratio of organic matter in the water column.

Urban development, like residential and road construction, and recreational use and maintenance around the lake will have increased the organic and inorganic (metals) inputs into the lake.

An important assumption is that the timing of the lake response to the above developments parallels the history of changing land-use, and the magnitude of this response is proportional to land-use intensity.

1.4 Research question

Continuing the earlier stated ideas and hypotheses; it is most interesting to see:

Which developments in the state of the water quality of the Elk Lake ecosystem (Vancouver Island, B.C., Canada) over the past 150 years can be identified using paleolimnological approaches, and linked to historic records on natural and anthropogenic disturbances?

The above question can only be answered if the following sub questions:

- Can the paleolimnologically inferred trends in the Elk Lake water quality be validated for the last 20 years using the available water quality records?
- What were the properties of the Elk Lake system prior to or following natural and human disturbances?
- Was the Elk Lake ecosystem relatively stable prior to disturbance, or were there significant trends or fluctuations in some of its properties?
- What has been the pattern of recovery from disturbance, and was the prior state re-established?
- What is the nature and magnitude of natural variability, and the frequency of unusual extreme conditions?
- Do anthropogenic disturbances have effects that are different in degree or kind from those of natural disturbances?

The main focus of this project is a paleolimnological assessment of the effects of anthropogenic activities on the water quality of the Elk and Beaver Lakes over the past 150 - 200 years. It consists of three parts (see Figure 1):

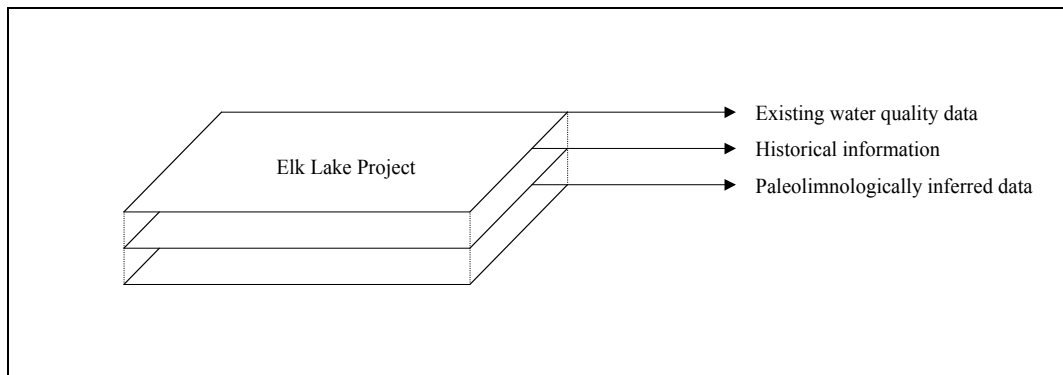


Figure 1.1: Visualisation of the project's design.

First, the existing sets of water quality data collected in the Elk Lake watershed over the past decades will be brought together from numerous sources, and will subsequently be evaluated.

Secondly, the historical changes that occurred in the Elk Lake watershed area over the past 150 years, with special attention to residential, agricultural and infrastructural developments that might have affected the aquatic ecosystem, will be researched.

Third, the sediment cores that were taken from Elk Lake will be analysed (sediment composition; diatom species composition) and dated using the ^{210}Pb -dating historical method.

1.5 Objectives

In this research project we will try to discern how Elk Lake has changed as the result of natural disturbances and anthropogenic activities in (and outside) its watershed area. At the end of the project:

- The water quality development of the Elk Lake system over the past 150 – 200 years will be reconstructed using paleolimnological techniques;
- Known recorded natural and anthropogenic disturbances will be linked to the discernible biological or chemical changes in the composition of the lake ecosystem, and their effects compared;
- From all the gathered information, recommendations for sustainable management of Elk Lake will be extracted.

All of the above aspects will be touched upon in separate chapters discussing specific parts of the paleolimnological analysis of Elk Lake.

2 The Elk Lake watershed: past & present

2.1 Location

Elk Lake is situated on the southeastern tip of Vancouver Island, BC, Canada. Located in the greater Victoria area, influenced by different kinds of anthropogenic activities, and under constant pressure from the recreational activities undertaken on and in both lake and watershed, Elk Lake has been and still is a unique and ideally situated research lake.

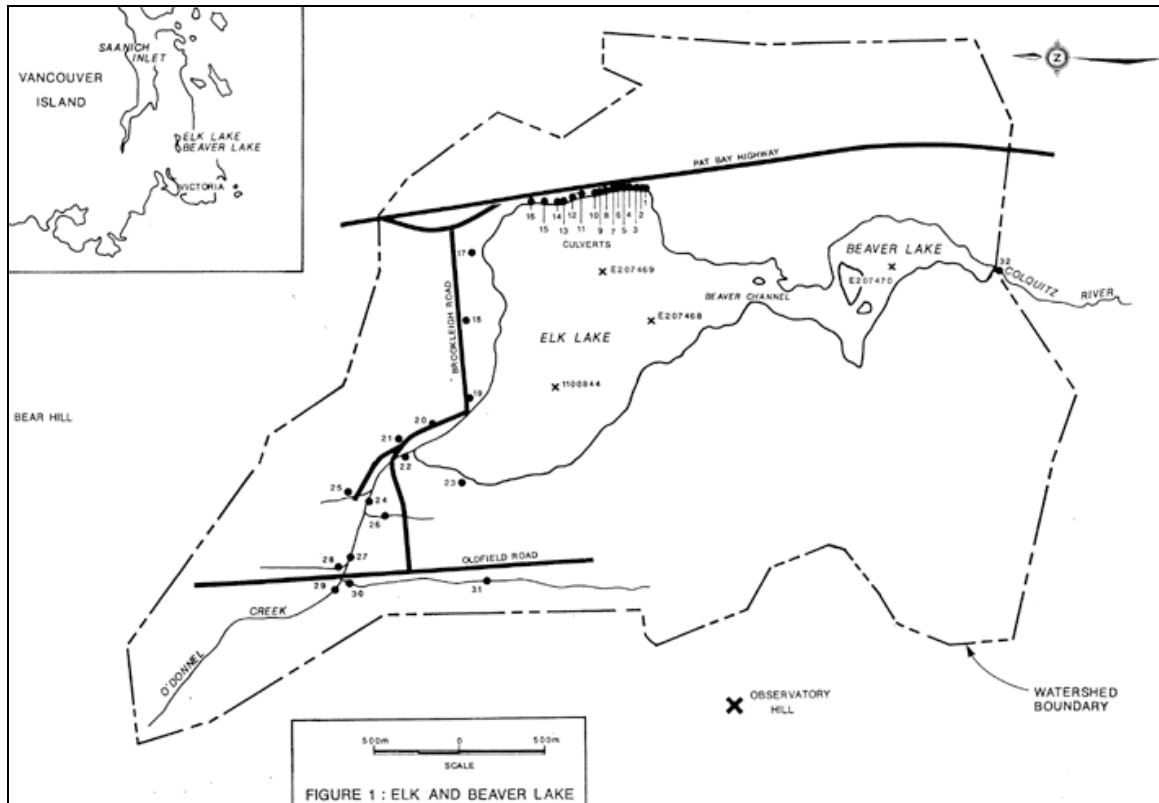


Figure 2.1: Location of Elk Lake watershed on the southeastern tip of Vancouver Island, BC, Canada (Holms, 1996)

The water body is located on the Saanich Peninsula of southern Vancouver Island, approximately 8 km north of Victoria. Its drainage basin lies within the coastal Douglas fir biogeoclimatic zone, which has mild wet winters and dry summers (McKean, 1992).

2.2 History of the Elk Lake watershed

2.2.1 Historic usage of the water from Elk & Beaver Lake

In the historical records, Elk and Beaver Lake first appeared on a Hudson Bay Company map published in 1855. Not long after that, in 1872, Elk Lake was recommended as Victoria's main domestic water source by Thomas Buckley, the provincial government's chief surveyor (CRD Parks, 1993). Between 1873 and 1920 the City of Victoria used the lake system as a source of domestic water. The supply system for the city was completed

in 1879. By 1908, the water demand in Victoria was in excess of 9,090,909 L per day. The Elk Lake supply soon became inadequate to meet the needs of the city's population. In 1914, the lake was abandoned as city water supply source, but remained in local use until 1920.

In 1942, a pumping and filtering station was established to supply water to the Patricia Bay Air Force Base. The system was turned over to the Municipality of Central Saanich in the late 1950's with the proviso that water be supplied to North Saanich, Sidney and Swartz Bay Ferry Terminal (Oliver, 1972).

The water pumped from Elk Lake rose from 340 dam³ per year to 900 dam³ per year between 1962 and 1975 (Comeau, 1976). The supply was augmented over this period by wells and by 1976 Elk Lake supplied only 30-50% of the supply to the north part of the Saanich Peninsula (Brown, McDougall and Dakin, 1976). In 1977 the Greater Victoria Water District extended its pipeline to the north part of the peninsula and Elk Lake ceased to be used as a supply for water (Nordin, 1981).

For the last 25 years, Elk Lake waterbody has primarily functioned as a recreational lake.

2.2.2 Hydrological changes in and around Elk Lake

The Elk & Beaver Lake water basin has undergone some drastic developments in the last century and a half. Probably one of the most important developments influencing the lake system was the construction of the Victoria waterworks between 1873 and 1879. It resulted in an increase of the lake's surface area and volume. The construction of the Patricia Bay Highway in the 1950's may have had a serious impact too, but there is no research available identifying the individual effects of either event. Neither are there any records on the effects of the settlement of the Elk Lake watershed.

In regards to the different hydrological changes, 1993's Natural Resource Inventory of Elk/Beaver Lake and Bear Hill Regional Parks contains a comparison of the situations in 1859 and 1982. It concluded that principal hydrologic features were dramatically altered since the end of the 19th century:

- The surface area expanded 21%, from 184 to 223 hectares;
- The shoreline perimeter increased nearly 19%, from 7920 to 9390 metres;
- Notable was also the disappearance of many small streams;

In this case, expansion of the surface area and the increase of the shoreline perimeter must also have meant a lake level rise. The disappearance of small streams can probably partly be contributed to the construction of the highway, and the maintenance of the recreational area's and trails around the lake shore (Capital Regional District Parks, 1983).

2.3 Lake characteristics

The Elk Lake waterbody can be divided into three separate limnological areas: Elk Lake, Beaver Lake, and the shallow channel separating the two basins (McKean, 1992).

O'Donnell Creek and its tributaries drain the northern part of the Elk Lake basin. This is the major inflow into Elk Lake, followed by 20 intermittent ditches and creeks which drain the north-eastern sub drainage. (Holms, 1996).

According to McKean (1992), the surface area of the complete waterbody is 246 ha (Table 1). In his report on the use of Elk Lake as a balancing reservoir for irrigation, Nordin (1981) also listed the lake and watershed characteristics as measured in previous reports on the watershed (Table 2).

Table 2.1: Morphology of Elk and Beaver lakes (McKean, 1992).

	Elk Lake	Beaver Lake	Beaver Channel	Combined
mean depth (m)	9.2	3.0	2.9	7.7
max. depth (m)	17.9	7.5	3.0	17.9
surface area (ha)	186.6	32.8	27.4	246
volume (dam ³)	17,143	990	801	18,834

Table 2.2: Lake and watershed area characteristics (Nordin, 1981).³

drainage area	995 ha ^[a] 621, or 825 ha ^[b] 1085 ha ^[d]
lake surface area	263.4 ha ^[a] 189 ha ^[b] 186 ^[c] 226 ha ^[d]
mean depth	7.63 m ^[a] 9.15 m ^[b] 8.8 m ^[c]
maximum depth	18.3 m ^[a] 16.7 m ^[b] 15.3 ^[c]
lake volume	15,815.5 dam ³ ^[a] 16,423,774 m ³ ^[b] 16,474 dam ³ ^[c]

According to that report, the water residence time varied between 4.3 and 11.9 years in the period 1977-1980. The mean water residence time was estimated at 7.5 years (Nordin, 1981). McKean (1992) measured a water retention time of 4.4 years for Elk and 0.25 years for Beaver Lake.

2.4 Water quality management

2.4.1 Recent water quality monitoring of Elk Lake

In 1968, a “Report on the Recreational Possibilities of Elk – Beaver Lake” was prepared for the local District of Saanich by P.B. Strogan Ltd. Consulting Engineers. The first signs of eutrophication of the lake were already visible during those years. In the 1972 “Limnological Study of Beaver Lake” N.R. Ringstad showed conclusively that Beaver Lake was becoming highly eutrophic (Natural Resource Inventory, 1993).

³ Sources: [a] Comeau, 1976; [b] Crane and Salmond, 1971; [c] Fish and Wildlife Branch Survey, 1971; [d] Johnson, 1952.

Regular monitoring at the deepest point of the Elk/Beaver basin started in 1986 to record the water quality developments, though water quality had been measured before this date. The three purposes for monitoring the water quality of the lake system were to identify:

- Long-term changes in water quality as a consequence of development within the watershed;
- How these changes may impinge on certain uses of water from the lake; and
- Attainment of water quality objectives.

Some of the data acquired from this program between 1986 and 1995 were evaluated by Holms (1996). In this report the state of water quality over that period was summarized: more than seven of the set criteria for protection of aquatic life, recreational use and human health for Elk and Beaver Lake were exceeded. In the British Columbia Water Quality Status Report (1996), the general state of the water quality in Elk Lake was reviewed as being borderline, that of Beaver Lake as being poor.

Table 3: Ambient water quality objectives for Elk and Beaver Lakes (McKean, 1992)

Temperature (hypolimnion max.)	15°C
Dissolved O ₂ (summer min.)	5 mg/L (1 m. above sediment)
Chlorophyll-a	1.5-2.5 mg/L
Secchi disc depth	1.9 m.
Phytoplankton community	No dominance (< 50% cells/mL) by Cyanophytes

McKean (1992) also noted that, around 1988, observations by the public suggested that the water quality in Elk Lake was deteriorating. This could mean that phosphorus concentrations in the lake system increased over this period. But no apparent trend was detected from the data on spring overturn phosphorus concentrations (collected over the period 1980-1990). Furthermore, no statistically significant trends could be discerned from the available water quality data for the period 1983-1998 (Ministry of Environment, Lands and Parks, 2000). Though in comparison with the 1996 B. C. Water Quality Status Report, the overall rating of Elk Lake slipped from borderline to poor when taking the 1993-1995 results into account.

2.4.2 Designated uses & objectives

The last couple of decades, Elk Lake has been characterized as a eutrophic system, with the accompanying yearly summer blooms of Cyanophytes, oxygen depletion of the hypolimnion, and high phosphorus and chlorophyll concentrations.

In the previously mentioned reports, recommendations were made on how to improve the water quality of the ecosystem. All centred on reduction of phosphorus loading by either:

- Controlling the internal phosphorus release from the sediment, for instance by aeration of the lake. Internal loading is the largest source of phosphorus, according to McKean (1992); or
- Reduce phosphorus loading from external sources, like O'Donnel Creek.

By reducing the phosphorus concentration, previously developed site-specific ambient water quality objectives⁴ for Elk Lake can be reached (McKean, 1992). Those are important because they are linked to the two types of water use that were identified for this system:

- Primary contact water recreation; and
- Aquatic life (with provisional objectives for cold water fishery).

The main goal of the objectives is to ensure that the future water quality is acceptable for the designated water uses. This acceptable water quality is defined by a set of limits and goals:

- Temperature shall not exceed a maximum of 15°C in the hypolimnion layer of the lake;
- Dissolved oxygen shall not be less than a summer minimum of 5 mg/L 1 m above the sediment in the lake;
- *Chlorophyll a* shall have a mean summer range of 1.5-2.5 g/L. The mean is determined from samples collected every four weeks from May to August at four depths (0, 2, 4, 6 m) in Elk Lake and at three depths (0, 2, 4 m) in Beaver Lake;
- Secchi depth, an indication of water clarity, must exceed 1.9 m;
- The phytoplankton community shall not be dominated by Cyanophytes. The number of Cyanophytes shall not exceed 50% of the cells/mL in discrete samples collected at the surface. These samples shall be collected every four weeks from May to August (Water Management Branch, 1996).

However, as has been stated earlier in this report, it would be useful to find out what the natural state of the lake was before human impact before remediation efforts are applied to the lake system. How paleolimnology, as a tool, can be used to learn more about an aquatic ecosystem's history is described in chapter 3.

⁴ Ambient water quality objectives are established for water-bodies on a site-specific basis. The objective can be a physical, chemical or biological characteristic of water, biota or sediment, which will protect the most sensitive designated water use at a specific location with an adequate degree of safety. The objectives are aimed at protecting the most sensitive designated water use with due regard to ambient water quality, aquatic life, waste discharges and socio-economic factors (Water Management Branch, 1986)

3 Paleolimnological techniques and approaches

3.1 Introduction

Paleolimnology, a synthetic and strictly interdisciplinary science, is defined from a limnologist's perspective as *'the interpretation of past limnology from changes that occurred in the ecosystem of the lake, and their probable causes'*. (www1)

It is the study of past freshwater, saline, and brackish environments. In some cases, the history of a specific water body is investigated; in others, information is collected and analyzed in a wider geographical and ecological context.

Nowadays, this is possible because modern techniques allow scientists to extract information on the historic conditions of an aquatic ecosystem via proxies contained in its sediments.

Over the course of time, these ecosystems have been altered in a number of ways by natural events and anthropogenic activities. Records of these alterations have been left in the sediments, which are relatively static derivatives of the dynamic ecosystems. This sediment record has been accumulating since the moment the system was created, thus it provides an archive of all the major changes the ecosystem has undergone. Through the proxy records, researchers interested in this history can establish how a system changed over time.

The paleolimnological approach has proven itself increasingly useful in the last decades because the underlying techniques have been improved and refined to such a level that they can be used to fill the gap of non-existent historic records on the state and development of aquatic ecosystems.

That is possible because:

- Information on historic conditions of a lake can be inferred from fossils, geological, and chemical signals contained in the sediment of the aquatic ecosystem.
- The data acquired using these techniques can often be used for quantitative and qualitative reconstructions of lake chemistry and biology (www2).

Water quality data collected in the last couple of decades is often useful for validation of inferred water quality developments.

In the next part of this chapter, the general theory behind the accumulation and composition of the sedimentary record is explained. The different paleoindicators currently used for reconstructions of ecosystem developments are touched upon in the following sub chapters. Furthermore, the common methods used for the dating of sediment cores are described. By combining all these techniques and methods, it becomes possible to infer usable information on the historic state of an ecosystem from the original sediment data.

3.2 *The Sedimentary Record*

3.2.1 Deposition and accumulation of sediments

Climate and regional geology control which materials sedimentate to the bottom of a lake. There biological processes of both the lake and its drainage basin modify them. Water movement, such as wave action and currents, sort particulate matter according to its size and density, and the energy available for displacement. The result is a general gradient from coarser particles near shore regions to finer particles in sediments under deeper waters (Wetzel, 1983). Such a record will have been accumulating for centuries, with different speeds, in different timeframes.

This accumulation of sedimented material has many attributes that make it useful archives. The most fundamental of these is summarized by the ‘Law of Superposition’, which states that for any undisturbed sedimentary sequence, the deepest deposits are the oldest, since they are progressively overlain by younger material. Hence, a depth-time profile slowly accumulates (Smol, 2002).

Such a dated depth-time profile can be linked to the composition of the sediment record, from which a variety of information can be inferred.

3.2.2 Composition of the sedimentary record

For paleolimnological analyses of sediment cores, the assumption is made that sediment stratigraphy is (relatively) undisturbed. If this is the case, and it can often be confirmed by a short visual inspection of the core, then it is possible to slice the core up into thin layers of sediment, which will each represent a certain time interval in the history of the sampled lake. These can subsequently be analyzed for a range of variables.

With the taking of a sediment core, the unknown history of the sampled lake ecosystem is starting to be opened up to the paleolimnologists. Contained in that sediment, different biomarkers, also called paleoindicators, are available to paleolimnologists for reconstruction of historic lake conditions. The fossil record of sediments includes both the biochemical substances produced by organisms, or resulting from their degradation, and morphological remnants of specific organisms (Wetzel, 1983). Some of the more commonly used paleoindicators are listed below:

- Pollen;
- Algal pigments;
- Soot & charcoal;
- Geochemical characteristics;
- Chironomid head capsules;
- Diatoms.

The decision to use certain indicators for paleolimnological research depends primarily on the goal of the project, and the usable paleoindicators discovered during a first inspection of a sediment core.

In section 3.3, the use of diatoms and chironomid in paleolimnological investigations is described in more detail. Other known paleoindicators are touched upon later in the same section.

3.3 Biological indicators

3.3.1 Diatoms

Diatoms (also known as Bacillariophyta) are unicells that are distinctly different from other phytoplankton. Their distinguishing feature is a cell wall made of silicon dioxide. This so-called frustule is composed of two valves, which fit together with the help of a set of girdle bands.

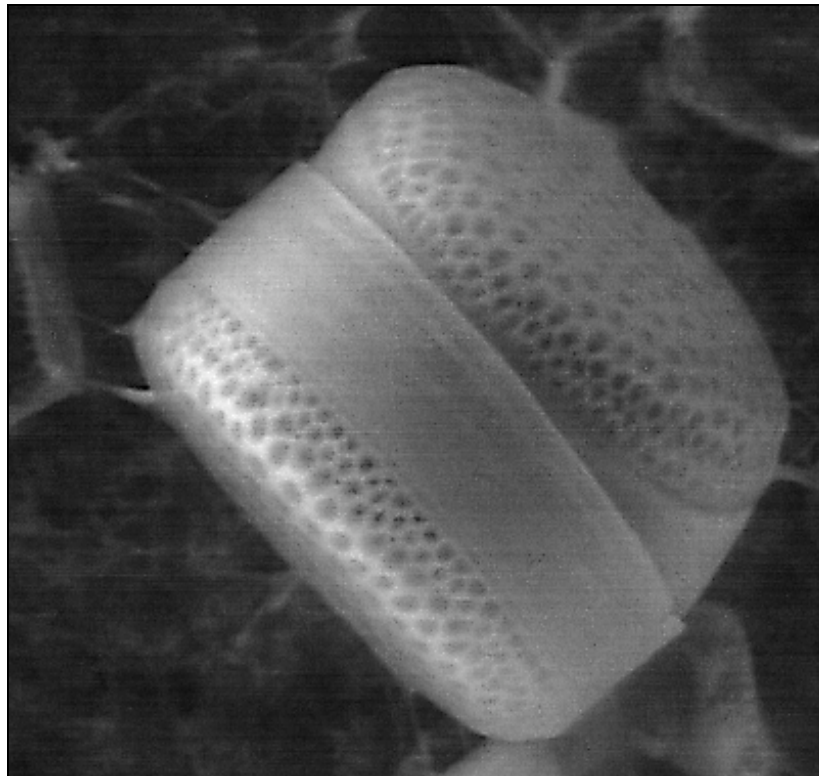


Figure 3.1: Electron microscope picture of a diatom frustule where the two valves have been pushed slightly askew.

In general, two major groups of diatoms are recognized:

- The centric diatoms, which exhibit radial symmetry and have oogamous sexual reproduction;
- The pennate diatoms, that are bilaterally symmetrical and produce ameboid gametes (isogamous) that are morphologically similar but may be physiologically different.

The taxonomy of diatoms is based on the shape and structure of the siliceous valves. Identification on a species level usually requires examination with oil-immersed objectives of permanently mounted specimens. When the diatoms are retrieved from a sediment core, oxidization of the organic components in the sample is necessary. That way, all view-obstructing components will be removed so only pure diatoms will remain. These can be dried onto a coverslip, and then mounted onto a glass slide using a mounting medium with a high refractive index.

Of the many biomarkers available to paleolimnologists, diatoms, and their (identifiable) remains, are the most widely used group of indicators for eutrophication research. This is mainly because:

- Their siliceous cell walls are resistant to dissolution and breakage;
- Diatom taxonomy is well defined, and the size, shape, and sculpturing of their valves are taxon-specific, making them easily identifiable using microscopic techniques;
- Many species have well-defined environmental optima and tolerances;
- They are present in almost all aquatic environments; and
- Fossil assemblages in lakes are often abundant and diverse (Dixit *et al.*, 1992).

The morphological remains of the individual diatoms in such fossil assemblages from a certain sediment layer can be identified and counted. This information, set off against knowledge about the environmental conditions that the identified species can tolerate, can be used to approximate the state of the ecosystem during the interval over which this layer accumulated.

The occurrence and relative contribution of certain diatom species to the total assemblage in a certain interval in the core can be used to infer the water quality in the water column laying on top of that specific part of the core at a certain moment in time. Several transfer functions linked to extensive lake data sets have been developed in recent years to facilitate the inference of water quality data from diatom assemblages present.

In section 3.5 the different methods currently in use for information inference from sediment characteristics are described

3.3.2 Chironomids

Subfossil remains of freshwater midges (Diptera: Chironomidae, Ceratopogonidae & Chaoboridae) are being increasingly valued as indicators of limnological and climatic changes (Walker, 2000). This is mainly because chironomids are among the most abundant macroinvertebrates in aquatic systems. Their head capsules, which are left in the sediments of water bodies, are:

- Abundant;
- Taxonomically distinctive; and
- Well preserved in lake sediments.

Chironomids also respond rapidly to changes in the trophic status of lakes, thus making them very useful proxies (Walker *et al.*, 1993; Hall and Smol, 1999).

They can be used to research a range of water quality variables. For instance, it has been suggested by Little *et al.* (2000) that chironomid assemblages respond more strongly to changes in deepwater oxygen availability than to epilimnetic nutrient concentrations, especially during pronounced periods of hypoxia.

Like many other aquatic organisms, larval Chironomidae are also sensitive to the osmotic stress imposed by waters of different salinities (Walker *et al.*, 1995).

3.3.3 Other biological proxies

Besides diatoms and chironomids, there are a number of other biological indicators that are often used by paleolimnologists. For instance:

- Charcoal analyses - to track different types of human activities. The smaller particles can be transported over long distances, thus providing information on regional fire frequencies. Larger ones are indicative of local wood burning (Smol, 2002);
- Biochemical substances⁵, like algal photosynthetic pigments. These are especially useful in situations where algal taxa didn't leave reliable morphological fossils. Specific pigments such as myxoxanthophyll, oscillaxathin and aphanizophyll, remains of blue-green algae, have been used to track nuisance populations of Cyanobacteria in lake eutrophication work (see Leavitt and Hodgson, 2001);
- Together, the microfossils of pollen and spores are referred to as palynomorphs. These are analyzed in a variety of fields, mostly focussed on reconstructing terrestrial vegetation. These investigations often have strong links to many questions posed by paleolimnologists, such as inferring changes occurring in the catchment of a lake;
- Stomatocysts, the siliceous resting stages and scales of the chrysophyte algae, are well preserved in sediments, and they may also be used as indicators of nutrient trends. In general, stomatocysts numbers are reduced in high-nutrient conditions in temperate lakes, so the ratio of stomatocysts to diatom valves can be used to track nutrient shifts (Smol, 1985).

3.4 Geochemical characteristics

Besides the listed and described biological indicators, which enable researchers to indirectly infer past conditions, geochemical characteristics are more a direct indication of the status of certain processes in the aquatic ecosystem or its watershed.

Looking at the geochemistry from a limnological point of view, chemical elements that can be detected in a sediment core may be classified in five different groups (Kemp et al. 1976):

- Conservative elements;
- Nutrients;
- Carbonate elements;
- Mobile elements;
- Enriched elements.

Major elements, like Si, Al, Ti, Na, K, Mg, Cl, whose content in the sediments is mainly controlled by the geochemical features of drainage basin, are considered to be conservative. Their concentrations are seldom affected by direct human influence to any noticeable extent.

Organic C, P and N are necessary for the growth of aquatic plants. Concentrations of nutrients and organic matter can be used to estimate the productivity of a system. Furthermore, the C:N ratio can be used to assess the relative importance of terrestrial and aquatic inputs into an aquatic ecosystem.

Carbonate C, Ca and the part of Mg not due to silicates, deriving from the weathering of carbonates in the watershed, or authigenically produced within the waterbody are called carbonate elements.

Controlled by pH and redox conditions certain elements may become mobile in the sedimentary environment. Examples of these are for instance S, Fe, and Mn

⁵ Biochemical substances: substances produced by organisms or resulting from their degradation.

These will undergo chemical changes, which influence their mobility (increasing or decreasing their solubility). Mobile elements may decrease when the hypolimnion becomes depleted of oxygen and redox conditions favor the reduction to more soluble compounds.

Enriched elements like Cu, Zn, Pb, Cr, Ni, Hg, As are widely used by man in industry, hence liable to be discharged at a rate that greatly exceeds the natural input.

3.5 ^{210}Pb sediment dating

Sediment dating techniques measure the decay of naturally occurring radioisotopes. For the dating of more recent sediment samples (up to ~ 150 years) the radioisotope of lead (^{210}Pb) in the uranium (^{238}U) decay series is the most commonly used.

^{210}Pb forms naturally in the sediments and rocks that contain ^{238}U , as well as in the atmosphere, a by-product of radon gas. Within 10 days of its creation from radon, ^{210}Pb falls out of the atmosphere. It accumulates on the surface of the earth where it is stored in soils, lake and ocean sediments, and glacial ice. The ^{210}Pb eventually decays into a non-radioactive form of lead. ^{210}Pb has a half-life of 22.3 years, which means that after 22.3 years, only half of the original amount is undecayed. If the sediment layers are undisturbed, then as the sediment ages it slowly loses its radioactivity. We can determine how old a sediment layer is by how much ^{210}Pb it contains. It takes about 7 half-lives, or 150 years for the ^{210}Pb in a sample to reach near-zero radioactivity.

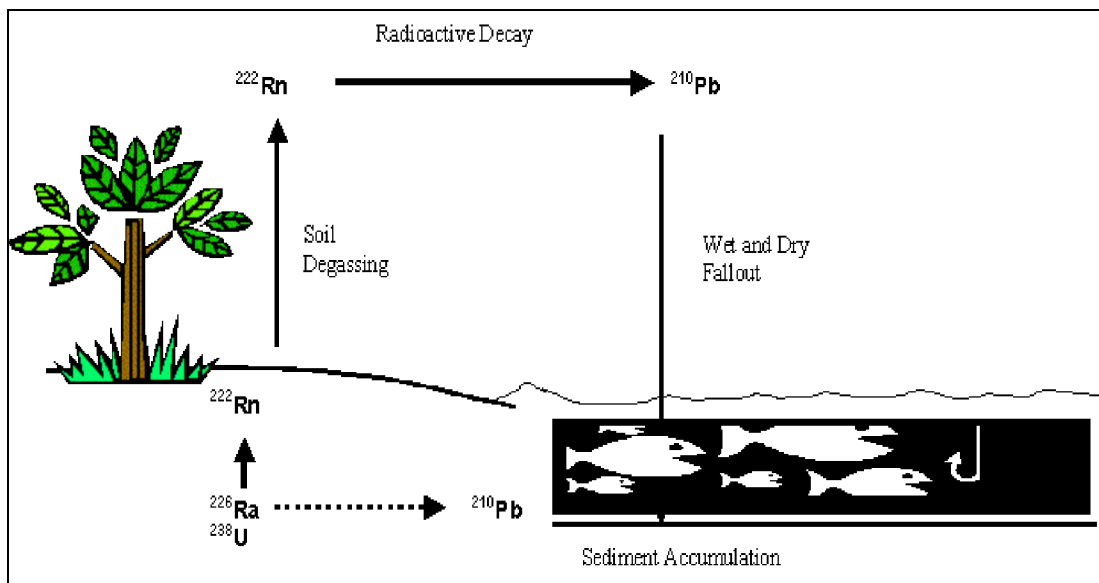


Figure 3.2: Pathways of isotopes in the radioactive decay series of ^{238}U (Mycore, 2000).

The dating of sediments is essentially the measurement of the concentration of ^{210}Pb in the sample. There are three methods available to achieve this. Of these, the most frequently used one is the measurement of ^{210}Po (a granddaughter of ^{210}Pb) by alpha spectrometry. Detailed descriptions of these methods and techniques are presented in Flynn (1968) and Evans and Rigler (1980), with modifications described in Cornett et al (1984) and Rowan et al (1995).

Using the ^{210}Pb -dating method the age of the different parts of the sediment core can be determined. This, together with the cumulative dry weight, can be used for estimating the sedimentation ratio or changes in sediment mixing over a certain time frame.

3.6 Recent Paleolimnological Projects

Paleolimnological techniques have been used in numerous studies to assess the impact of natural (climate) and cultural impacts (logging) on lake systems. The study of algal remains (especially diatoms) has allowed reliable reconstructions of historical trophic status in British Columbia (Walker *et al.*, 1993; Reavie *et al.*, 1995a, 1995b; Hall and Smol, 1992), as well as many other regions (reviewed in Smol and Hall, 1999).

For example, Laird *et al.* (2001) evaluated the changes in lakes due to forestry activities using diatom-inferred total phosphorus and chironomid-inferred hypolimnetic oxygen levels. Their data suggested that logging has had an effect on lake systems, but that natural variability can be as large as the changes seen before and after the onset of logging.

In another area, Quinlan *et al.* (1998) showed in a recent study that subfossil chironomid assemblages could be related to the anoxic factor⁶.

By comparing quantitative paleolimnological inferences of diatom-inferred total phosphorus and chironomid-inferred hypolimnetic oxygen levels with historical records for Gravenhurst Bay (Ontario), Little *et al.* (2000) were able to show that surface and deep waters of the water body were decoupled following recent mitigation efforts.

Rhodes and Davies (1995) investigated the impact of watershed disturbance on a small oligotrophic lake in Maine over the last 3500 years by examining changes in geochemistry and organic matter. They concluded that increases in pH following disturbances were indicative of increased inputs of base cations from wood ash and mineral soils.

⁶ Anoxic factor: the number of days per year in which a sediment area equal to the surface area of the lake was overlain by anoxic waters (< 1 mg O₂/L).

4 Materials & methods for sediment and diatom analysis

4.1 Introduction

In this chapter, the procedures and protocols used to analyse the cored sediment samples, and count and identify the diatoms found therein are referred to or described. Furthermore, information about the collected water quality data for Elk Lake is given. General information about the location of Elk Lake watershed, its history and the lake characteristics can be found in the second chapter of this report.

4.2 Sediment core

4.2.1 Coring procedure

On 24 November 2001, three cores were removed from Elk Lake using a modified gravity corer, designed by dr. K.Telmer at the University of Victoria (see appendix D). All were taken from the deepest part of the lake, at a depth of approximately 19.4 meters, in the northwestern part of the Elk-Beaver basin (see figure 2.1, p. 9).

The three obtained cores were vertically sectioned into thin slices⁷ using a Glew extruder and preserved with nitrogen gas on the same day that they were taken. All samples were kept at -80°C until they could be further analysed.

Each of the cores was then used to measure one or more different variables:

- The first was sent off to MyCore (Deep River, Ontario, Canada) for ^{210}Pb dating of the age of all the slices;
- The second analyzed for geochemical characteristics by the Pacific Environmental Science Centre analytical laboratory;
- From the third, subsamples were taken and prepared so that diatom assemblages could be counted and identified.

The methods used with each of the three techniques mentioned above are described in the next three sections.

4.2.2 ^{210}Pb Dating of the sediment core sections

The first of the sediment cores was prepared following the directions provided by MyCore Ltd., which are described below:

- For the sections between 0 and 10 cm depth, samples with a dry weight of at least 100 milligrams were collected. Samples of +1000 milligrams were collected for the deeper sections;
- These samples are sub-samples of a homogenized part of the sediment core. Large pieces of extraneous material were removed prior to the preparation of the samples;
- Samples were dried, ground and then passed through a screen with about 100-mesh size;

⁷ The first 10 cm were sliced up into increments of 2.5 mm. From 10 to 30 cm, 5 mm slices were made. After that, the remaining part of the core was divided up into 10 mm sections.

- Consecutively, these were pre-weighed in 50 ml plastic centrifuge test tubes; All the samples were sent off to MyCore Scientific Inc. (Deep River, Ontario, Canada) for ^{210}Pb analyses.

There the samples were analysed for ^{210}Po (a product of ^{210}Pb in the radioactive decay series) using alpha spectrometry. The ^{210}Pb data can be accurately derived from these data. Consecutively, these were interpolated using the CRS (constant rate of supply) model of ^{210}Pb dating.

The sediment accumulation rates (SAR), the ages for each section as well as the uncertainty associated with the measurements were determined using this method. For those sections where the ^{210}Pb concentration wasn't measured, the ages and SAR's were interpolated and no uncertainty was estimated. Unfortunately, there was not sufficient ^{210}Pb excess to date the sections at the bottom of the core.

4.2.3 Geochemical analysis of the sediment

A second core was sent off to the Pacific Environmental Science Centre (PESC) in North Vancouver for analyses of the lake sediment. The sediment geochemical analyses were performed according to the methods documented in the Pacific Environmental Science Centre (1997).

Wet density, percentage dry weight and loss-on-ignition determinations were made using standard techniques.

Furthermore, for the following elements the concentrations were measured: Ag-T, Al-T, As-T, B-T, Ba-T, Be-T, Ca-T, Cd-T, Co-T, Cr-T, Cu-T, Fe-T, Hardness Total (T), K-T, Mg-T, Mn-T, Mo-T, Na-T, Ni-T, Nitrogen Total, P-T, Pb-T, S-T, Sb-T, Se-T, Si-T, Sn-T, Sr-T, Ti-T, V-T, Zn-T.

4.3 *Diatom Analysis*

4.3.1 Diatom preparation

The standard method developed by the P.E.A.R.L. group at Queens University (Kingston, Ontario) was used as a guide for the preparation of 20 sediment samples for diatom identification and counting (Wilson *et al.*, 1996). Furthermore, EPA's 'Standard Operating Procedure for Phytoplankton Analysis' (EPA, 1994) provided some useful information on how the Hyrax mounting medium had to be applied.

The used routine is described below:

- Homogenized sediment subsamples (wet: 0.700-1.200 g) were measured into 50 mL glass centrifuge tubes (or vials);
- (~10 mL) 10% HCl was added to each tube to oxidize carbonates, and left undisturbed for 24 hours before the remaining HCl was removed by aspiration;
- The vials were then placed in a support rack and ~15mL of a 1:1 mixture of concentrated nitric and sulphuric acid was slowly added up to the one-half or three quarter mark on each vial;
- The samples were stirred and left for at least 24 hours before being placed in a water bath (~90°C) for 3 hours;
- Afterwards, these were left to cool down overnight;

- On each of 6 consecutive days, the samples were stirred and aspirated down to 1 cm depth above the sediment, topped up with distilled water, stirred, and allowed to settle for at least 24 hours, until all acid was removed;
- A portion of the resulting slurry was then pipetted, in a series of dilutions, on to cover slips and allowed to evaporate on a hot plate;
- The dried cover slips were then mounted using Hyrax ® mounting medium (refractive index = 1.71). These were left to dry.

The slides had to be dry so they could be used on an inverted microscope with an oil-immersed objective.

4.3.2 Diatom Identification and Counts

On each of the prepared slides between 300 and 500 diatoms were counted using an Olympus IMT-2 inverted microscope, at 1000x and 1500x magnification. During the counts, all the counted diatoms were also identified, primarily using Patrick and Reimer (1966) and Cumming *et al.* (1995).

Consecutively, the relative abundance of each species or genus was determined by dividing the number of valves of the species/genus encountered by the total number of valves counted for on the slide.

4.4 *Water quality data*

Over the last decades, different government agencies have been sampling the water quality of Elk Lake. Their data, collected from 1983 onwards, has been retrieved from government databases for use in this project.

During the years of data collection, samples were taken at three locations. In the provincial database, SEAMS, these sites are referred to under the codes E 207468, E 207469 (Elk Lake) and E207470 (Beaver Lake).

The collected data was divided up into different sets for both the water quality and sediment data. These were arranged by date, so analyses for historical trends (per variable) would be easier.

5 Results of paleolimnological research

5.1 Introduction

Information generated by physical and chemical analyses of the sediment cores forms the basis of this research project. The dated core provides a time framework against which the chemical elements and biological indicators can be analysed and compared. This eventually leads to the generation of a comprehensive set of data describing (the developments in) an aquatic ecosystem. That set of data is presented in this chapter, starting with an analysis of the Elk Lake cores..

5.2 Sediment core

5.2.1 Visual inspection of the sediment



A first inspection of the taken sediment cores showed that all three cores were comparable. Until a depth of about 34 cm, (about 1633 A.D.) the cores are quite homogenous in structure and colour. Below that level, the colour of the sediment changes to a lighter brown and the sediment to a finer grain.

This can be explained if the input of (organic) matter into the lake was distinctly different before that time. The effects of this change become more apparent when profiles of the ^{210}Pb count and the different metal and nutrient concentrations are placed next to it (see sections 5.2.2 and 5.2.4).

Figure 5.1: Picture of two of the three Elk Lake cores (24 November 2001).

5.2.2 ^{210}Pb dating of the core

The ^{210}Pb profile shows a decrease in activity from the top layer of the sediment until a depth of 36 cm (Figure 5.2). After that, it starts to rise again. A different pattern is noticeable between 0 and 8 cm depth. The concentration of ^{210}Pb in these sections is very constant. This could indicate strong physical mixing in the core. In addition, from a general view, the Pb-210 concentrations are a bit lower than what you see on average (pers. comm., MyCore Scientific).

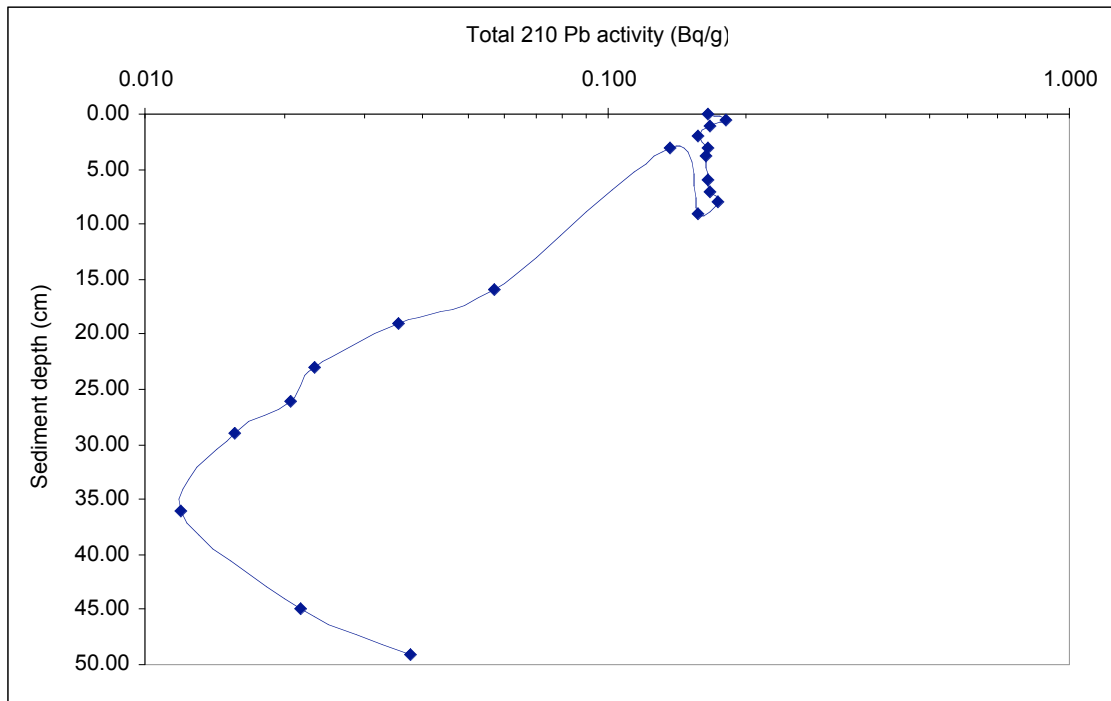
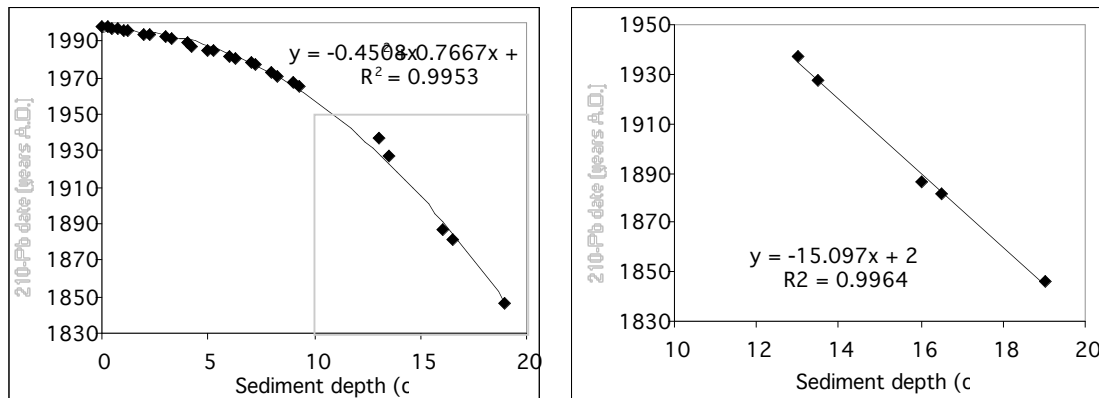


Figure 5.2: Total ^{210}Pb -Pb activity (on a logarithmic scale) over the depth of the sediment core.

Plotting the age of the sediment (in years A.D.) against the sediment depth (figure 5.3a) gives an indication of the changes in sedimentation rates over the past two centuries. The upper 10 cm accumulated over a period of about 40 years, the following 10 cm are the result of about a century of sedimentation. In the next section, the sediment accumulation calculated using the CRS model is presented.

The lead-210 dating method was not sufficient for dating the deeper, older parts of the sediment. After reviewing the available data, it was decided to extrapolate the ages for the older part of the core, where sediment depth vs. ^{210}Pb date displayed a linear trend. An approximate date for the deeper sections of the core could be inferred using that method. This instead of using the equation connected to the polynomial trend line visible in the figure on the left.



Figures 5.3a (left) and 5.3b (right): Sediment depth against the age of the sediment section (210-Pb dated) for the period 1830 - 1990.

5.2.3 Sediment accumulation rate

After a first inspection of the sediment accumulation data in Elk Lake during the last two centuries, which were calculated using the constant rate of supply model (Binford, 1990), the following things were noticed:

- The sediment accumulation rates are slightly higher but typical of what can be seen in other systems (pers. comm., MyCore Scientific);
- The sediment accumulation rate declines in the deeper parts of the core. This is typical of systems that were deforested or perturbed by human activity in recent times.

The last observation falls in line with what was hypothesised in the first chapter. Elk Lake is situated in an urban area, so anthropogenic perturbations are to be expected.

The CRS sediment accumulation rate (SAR) was plotted against the age of the sediment in figure 5.4. Some unverified trends were emphasized by placing thin 'help' lines. It seems the SAR was slightly increasing before the mid of the 19th century, after which rates increased almost exponentially.

At least from around 1858, human activities will have influenced the Elk Lake watershed (see Appendix A). Because there is no information on the rates of sedimentation before that time, it is unclear if those were already on the rise before settlers arrived in the watershed.

The almost exponential increase of sedimentation rates after the 1950's is a common sight. The industrialization and intensifying agricultural practices during and after that decade resulted in increasing nutrient inputs into and consecutive eutrophication of aquatic systems in the industrialized world.

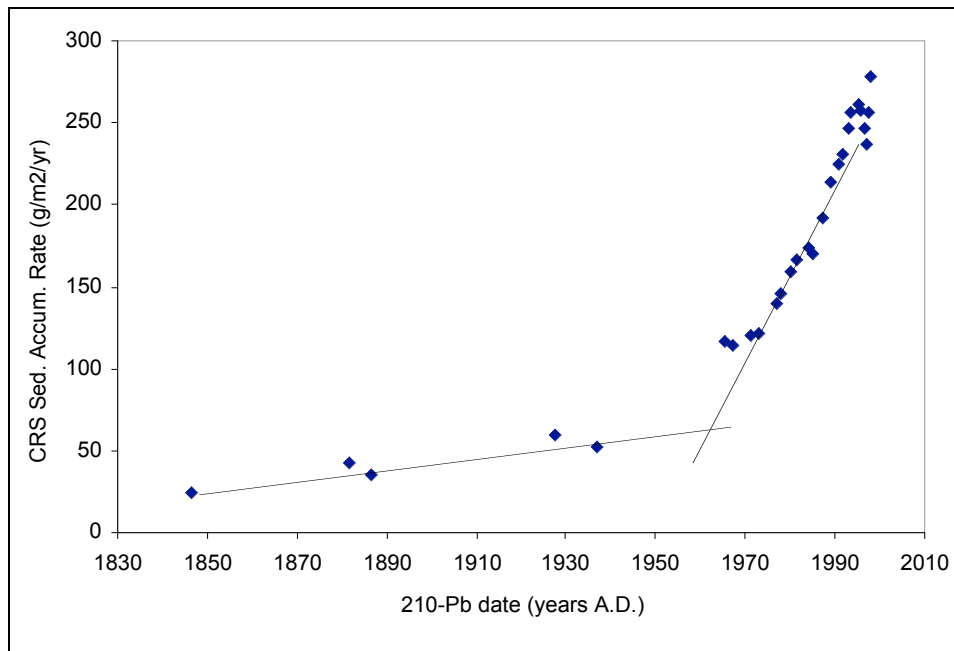


Figure 5.4: The sediment accumulation rate in Elk Lake over the past 160 years.

5.2.4 Geochemistry

5.2.4.1 Inorganic chemistry

In the Elk Lake sediment core, a variety of elements was measured. The total concentrations of Ag, As, B, Cd, Mo, Sb, Se and Sn were all below the detection limit throughout the core. These are therefore not touched upon in the remaining part of this chapter.

Of the other elements, titanium is one of the most inert ones found in nature. It provides an excellent reference for comparisons with more mobile or reactive elements found in the same samples.

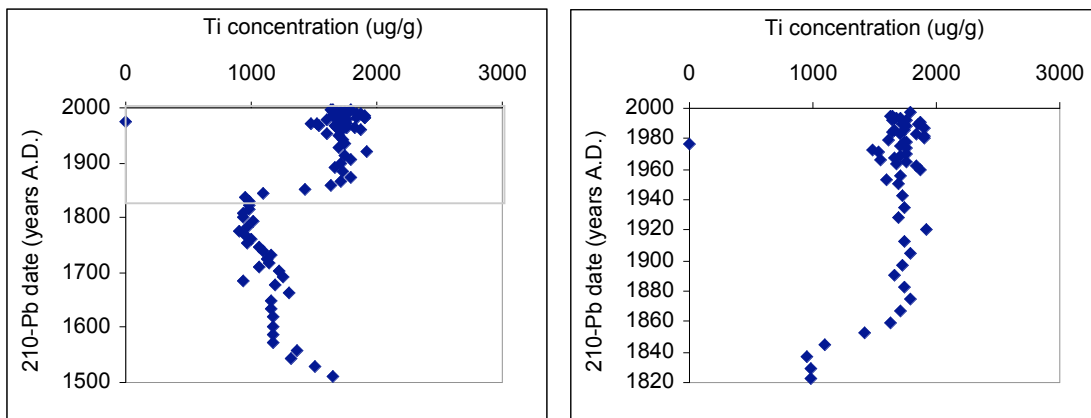


Figure 5.5a and 5.5b: The titanium concentration in the sediment over the past centuries.

The trend shown by the titanium concentration over the length of the core (see figure 5.5a), which spans approximately 5 centuries, is characteristic for the more conservative metals found in the core. From around 1500 A.D. onwards, there is a decrease in levels found in the core. Between 1600 and 1800, the levels are more stable or only slightly decreasing. The sudden doubling of concentrations between 1840 and 1870 has to be the effect of land-use changes in the watershed. At least there are no records of other long-term activities occurring in that area at that time.

5.2.4.2 Organic chemistry

Carbon and nutrient concentrations in sediments provide an insight into the (historic) productivity of an aquatic system. Although nutrients and organic compounds are constantly being used up and generated by different biological, physical and chemical processes occurring in the lake, they still provide a wealth of information.

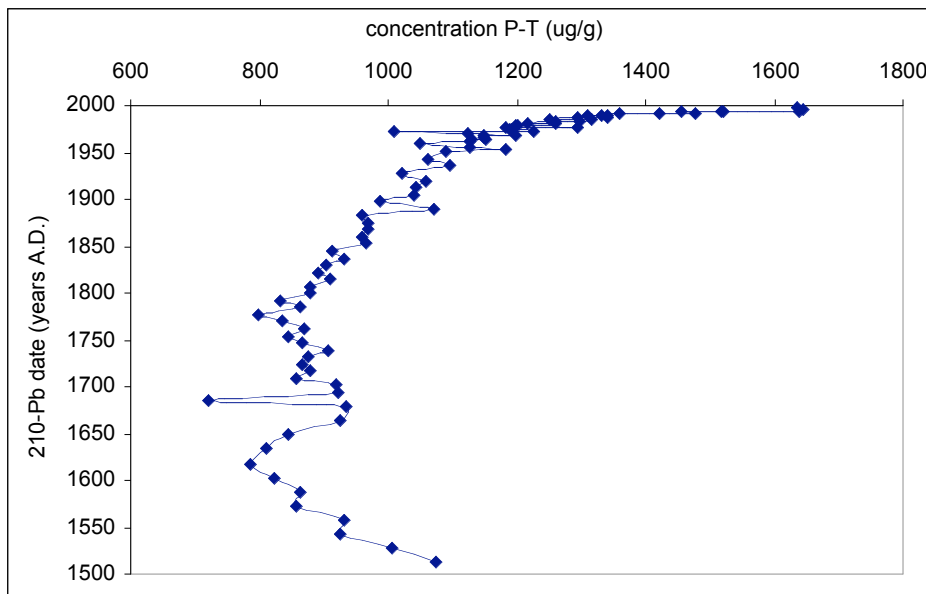


Figure 5.6: The total phosphorus concentration in the sediment core.

For instance, although the profile of phosphorus in the lake sediment (figure 5.6) shows a pattern characteristic for the mobile element, it still provides extra information on the historic conditions in and around Elk Lake.

Because the mobile phosphorus migrates upwards under anaerobic conditions, concentrations measured in a certain section of the core cannot be linked to the ^{210}Pb -determined age of that section. However, the distinctly higher concentrations in the lowest part of the core (1500 - 1600) indicate that the deeper part of the core, with a different structure and colour, also contains relatively higher phosphorus concentrations.

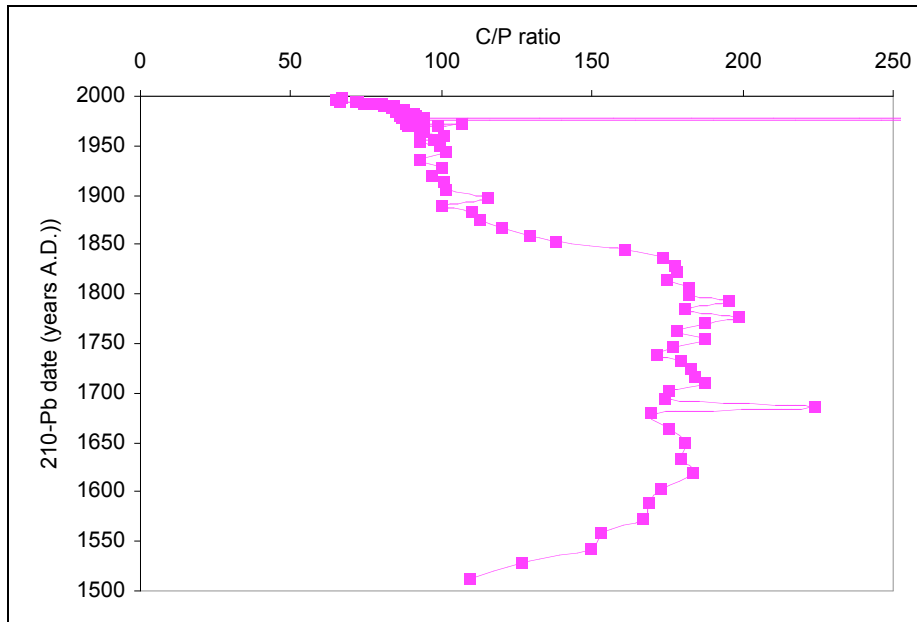
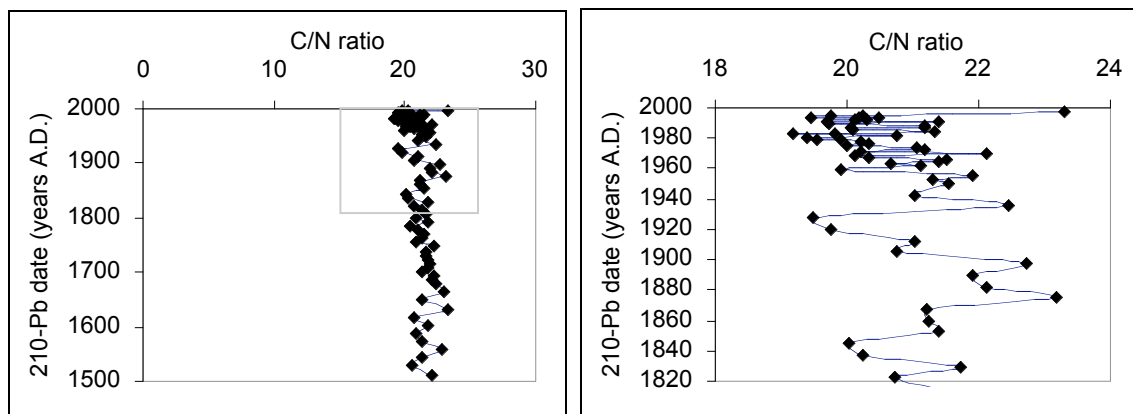


Figure 5.7: The C:P ratio in the Elk Lake core.

The difference in concentration is also visible in the profile of the C:P ratio (figure 5.7) around that time interval.

The C:N ratio gives an indication of where the organic material in the water column originates. Over the years, the C:N ratio in Elk Lake stayed quite stable, only slightly decreasing over the centuries from a level of around 22 to 20. This indicates that the fraction of organic matter settling from the water column over these centuries originated from comparable sources in comparable proportions.



Figures 5.8a and 5.8b: The C:N ratio in the sediment of Elk Lake.

When looking at the last 180 years, the decrease in the C:N ratio between 1880 / 1900 and 1925 is noticeable. This may be due to the creation of the Victoria waterworks and the subsequent use of Elk Lake as water supply.

5.3 Diatom species composition and stratigraphy

From a selection of sediment core sections, microscope slides were prepared for diatom counts and identification. The results hereof can be found in appendix D. Identification of all counted diatoms happened to species level where possible, and otherwise to genus. The relative abundance of the unidentifiable diatoms never exceeded 10%, and was usually below 5%.

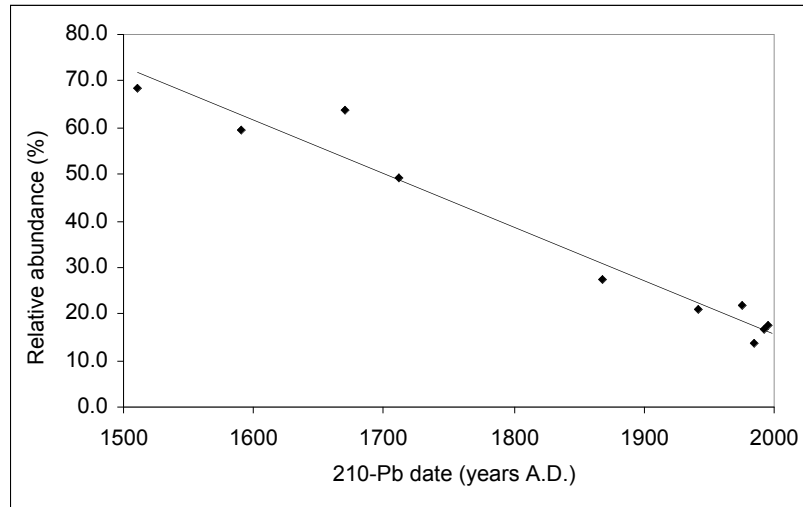


Figure 5.9: Relative abundance of *Aulacoseira sp.* in the 210-Pb dated Elk Lake core.

One of the first visible trends is the decline in relative abundance of *Aulacoseira sp.* over the last 4 or 5 centuries (see figure 5.9). Before the second half of the 19th century, *Aulacoseira* dominated the diatom population in Elk Lake. At certain points in time more than 50% of the population was comprised of this genus. After this period the contribution of *Aulacoseira* to the total population dropped to about 15 - 20%, thereby remaining one of the dominant genera/species in the lake.

In another case, Kilham *et al.* (1986) noted that the success of *Aulacoseira* was closely associated with erosional supplies of catchment-derived silica. This might also be the case here.

Compared to that, the relative abundance of quite some other recognizable genera and species shows a very different pattern (see figure 5.10):

- *Fragilaria crotonensis*, *Tabellaria sp.* and *Stephanodiscus sp.* abundances each start to increase between the start of the 18th and the end of the 19th century;
- In the 20th century, that increase continues exponentially for *Tabellaria*. This trend may be connected to other developments in the watershed. (see fig 5.11);
- Both *Stephanodiscus* and *F. crotonensis* maintain the same level of abundance throughout that century. In the last 10 - 15 years, their relative abundance seems to increase. This may be connected to the perceived deterioration of the water quality of Elk Lake by the public.

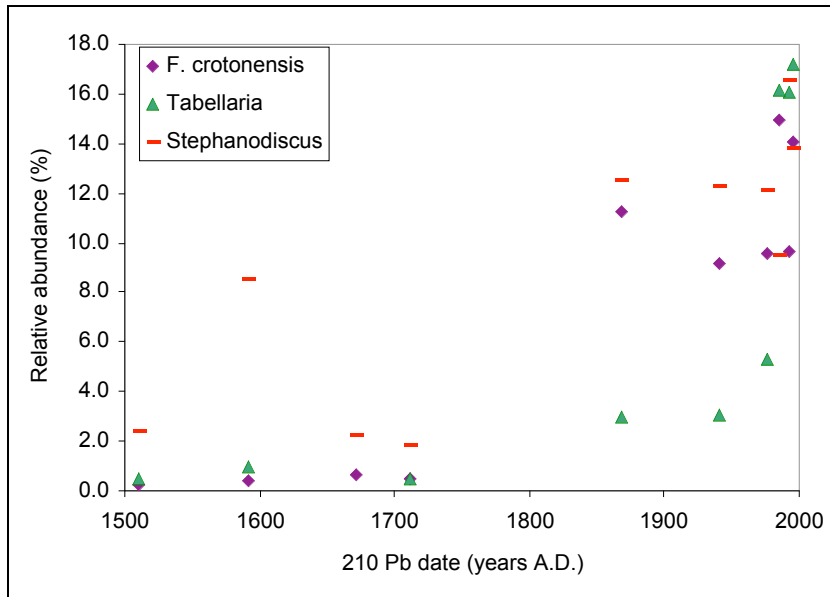


Figure 5.10: The relative abundance of *Fragilaria crotonensis*, *Tabellaria* and *Stephanodiscus* over the past centuries.

Something to note is the fact that although *Fragilaria* taxa tend to be ubiquitously distributed (Patrick and Reimer, 1966), they were often found in slightly eutrophic BC environments (Reavie *et al.*, 1995).

When looking at the other data in more detail again, it appears that there is a relationship between the relative abundance of *Tabellaria sp.* and the sediment accumulation rate over the past 150 years.

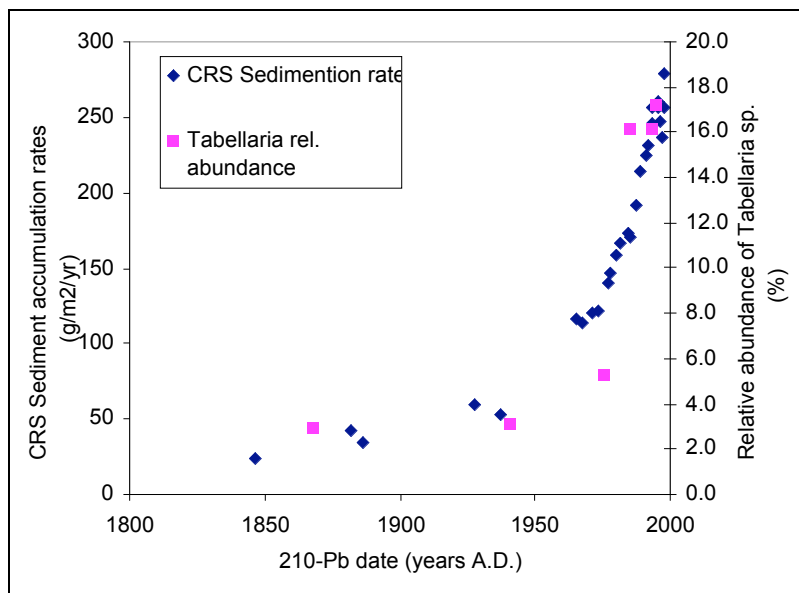


Figure 5.11: Relationship between sedimentation rate and relative *Tabellaria* abundance.

This might be a coincidence, but it is likely that due to an increase in nutrient inputs the *Tabellaria* population is also increasing and thereby contributing to increasing sedimentation rates of organic matter.

5.4 Water quality developments

5.4.1 Two decades of Elk Lake sampling

Besides all the data collected from analyses of the sediment cores, existing water quality data on Elk Lake were brought together from different government ministries and institutions. These provide a first reference against which other data can be compared.

After the structuring of this set of data, it became clear that it contained two decades of information for some variables and only 5 years for others. Below, the specific situations or visible trends over the period 1990 – 2000 are summarized per variable:

- Over the last decade, the chlorinity stayed between 14 and 16 mg/L;
- During the same period, the alkalinity stayed between 50 and 55 mg/L;
- The hardness between 50 and 70 mg/L (~60 average);
- The pH varied from 7.5 to 8;
- Sodium levels varied between 8 and 10 mg/L (~ 8.8 average);
- The potassium concentration was 1.5 mg/L on average;
- The average Ca^{2+} concentration was 17.2 mg/L, varying between 15 and 20;
- Of the total carbon concentration (on average 18.2 mg/L), more than 90% is present in dissolved form;
- On average, total phosphorus and nitrogen concentrations were 0.22 (0.005 – 2.0) and 0.6 (0.4 – 1.0) mg/L, respectively;
- Sulphate concentrations varied between 8 and 12 mg/L;
- Turbidity varied between 0.6 and 1.3 NTU;
- Magnesium levels stayed around 4 mg/L during that decade;
- Oxygen concentrations displayed profiles indicative of a stratified water column (fig 5.12).

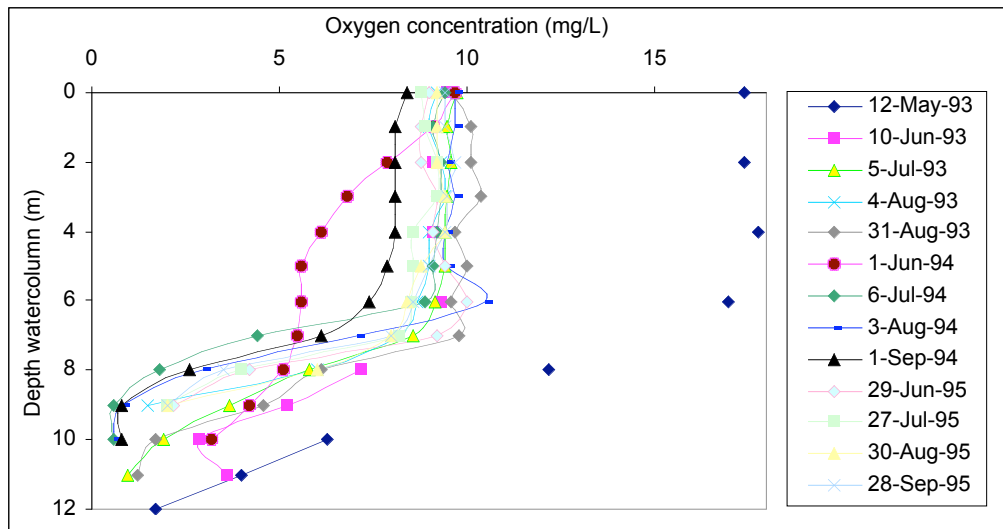


Figure 5.12: Oxygen profiles for Elk Lake over the period May 1993 – September 1995.

Most of the collected data measured during the past one or two decades didn't display a directly noticeable trend. But this will be further discussed in the upcoming chapters.

6 Discussion

6.1 Inferred water quality trends from a 210-Pb dated sediment core

6.1.1 Interpretation of sediment data

In the previous chapter, the results of the paleolimnological study of Elk lake were presented. There are some comments and additions to make to the analyses visualized and described therein.

The first 5 to 10 cm of the core should not be used in further analyses. Due to physical mixing (see fig. 5.2) in the top part of the sediment, this data cannot be considered useful, except when one is studying the lake's history in less detail over a much larger period.

As mentioned before, the ^{210}Pb -dating of the core can be accurately used for sediment samples younger than 150 years. Because this provided us with ages for less than 50% of the core's length, the dates were extrapolated to cover the entire core. Therefore, all dates before 1840 should not be considered accurate but only useful for clarifying or underscoring larger trends continuing into the 20th century.

The problem of diagenetic changes in organic compounds after deposition should not be underestimated either. Little is known about these processes, but the problem is that these transformations can be confused with those resulting from succession or changes in the pattern of organisms that synthesize them (Wetzel, 1983). Because this project covered a short time frame, where diagenetic changes are slim to none, the effects of such processes could be ignored.

6.1.2 Diatom identification & counts

One of the main issues with this project was the lack of information on the counted and identified diatoms. For a set of sediment subsamples the relative abundances of all present diatoms were determined, but often only to the genus level.

Another possible issue was the use of benthic and planktonic algae together. Some authors have already argued that it would be more appropriate to base predictive models solely on planktonic species that inhabit the open water habitat. This is mainly because the nature and distribution of the substratum with respect to light and depth affect the response of benthic algae to changes in water-column nutrients. In addition, fluxes from the sediment can greatly enhance the nutrient supply for benthic diatoms.

Recently, Philibert and Prairie (2002) concluded that including benthic species in predictive models doesn't significantly affect the predictive capabilities of those models.

6.2 *Measured vs. inferred water quality data*

6.2.1 Comparison of data with other projects

When comparing water quality data retrieved from Elk Lake with data from other lake systems, it is important to be aware of the fact that the drainage area of Elk Lake is unusually small relative to the size of the lake (Capital Regional District Parks, 1983).

On another note, inferred environmental conditions can be over- or underestimated when the lake data set against which results are compared mainly consists of more eutrophic or oligotrophic lakes. Unfortunately, during this project there was insufficient time for detailed inferences of water quality data from information present in the sediment.

6.2.2 Representability of the data

Even without having inferred water quality data, there are some other points where caution is necessary. The Elk Lake data sets available from previous sampling campaigns and research projects are all lacking in the sense that, for most years, there is no data available on the water quality of Elk Lake for the period June – September (Nordin, 1981). When this data is used for extrapolation of a certain trend, it cannot be assumed that extrapolated data outside the June – September period are realistic.

Furthermore, because the collected water quality data came from different sources, it is possible that methods used to analyse the quality of the water samples were not exactly the same.

6.3 *Connecting historical information with (inferred) data*

From a selection of sources, information on the history of the Elk Lake watershed was collected. The most important of these were:

- The Saanich Community Archives⁸;
- Elk/Beaver Lake and Bear Hill Regional Parks – Natural Resource Inventory (Capital Regional District Parks, 1983);
- State of water quality of Elk and Beaver Lakes, 1986-1995 (Holms, 1996); and the
- Preliminary report on the use of Elk Lake as a balancing reservoir for irrigation: possible effects on limnology, water quality and fisheries (Nordin, 1981).

Although a lot of information was collected this way (see Appendix B), this project would have benefited from more data on the land use changes in the Elk Lake watershed between 1850 and 1990.

The three different sets of data (historic events, sediment inferred data, water quality) all provided a different level of detail, and that made it difficult to connect them for the entire researched period. Due to this, conclusions were hard to extract from the available results.

⁸ Information about the Saanich Archives can be found on the web: <http://www.gov.saanich.bc.ca/community/heritage/archives.htm> or by phone: (250) 475-1775.

7 Conclusions & recommendations for Elk Lake

7.1 Large developments affecting Elk Lake's water quality

The contents of the sediment cores provide two different views on the Elk Lake history, depending on the time frame through which one looks upon the data. That can be over:

- 1) The full length of the core (approximately 500 years);
- 2) Only the accurately ^{210}Pb dated part (the last 150 years).

The most apparent trend for both periods is the doubling, tripling or even quadrupling of metal concentrations in the sediment core during the second half of the 19th century (see fig. 5.5b). This is most likely caused by land use changes in the watershed following the settlement of nowadays Greater Victoria area. These must have affected erosion and leaching of elements from soils, causing the concentrations in the lake sediment to rise.

By extrapolating the dates of the ^{210}Pb dated part of the core to the older part, a less accurate date reference of the second half of the core can be created. Here, the earlier noted increase of element concentrations is counterbalanced by an equivalent concentration decrease in the oldest part of the core (see fig. 5.5a). This trend is apparent for most elements that are not mobile in aquatic sediments.

As fig. 5.1 shows, the brown type of sediment visible in the deeper parts of the core was replaced by a darker type. Both this colour change and the decreasing concentrations for the different elements during this period were probably caused by an event that had a broad impact. This may be the 16th century megadrought that occurred across much of North America. It is described as perhaps the worst drought in the last 2000 years (Stahle *et al.*, 2000). It remains somewhat unclear what kind of effects this climatic variation had on the lake level, aquatic and terrestrial vegetation, and the (competition between) organisms.

If the success of *Aulacoseira* (fig. 5.9) from this period onward can be explained by the availability of catchment-derived silica, the higher concentrations of heavy metals in the deeper part of the core may also be the effect of soil and (or) sediment changes caused by the climate extreme. For this project, available data and collected information are insufficient to explain the mechanisms behind the involved processes

What has become clear though, is the fact that the Elk Lake watershed hasn't experienced a prolonged period of ecological stability in the past 500 years. This also indicates that the effects of natural extremes can be of the same order of magnitude as human disturbances. Due to these, it is impossible to analyse the resilience of the system.

Furthermore, the large-scale fluctuations also interfere with the assessment of the natural properties of the Elk Lake system. These reference values would be very useful for the present watershed management. However, what can be stated is that the system would contain less heavy metals and be less eutrophic if settlement of the Greater Victoria area hadn't occurred.

7.2 Inference of detailed water quality trends

On a more detailed level, the analysis of the data was more complex and sometimes not possible because of the limitations of this project. It is interesting to see the connection and time lag between the actual increase of sedimentation rates (fig. 5.4) and collected observations of the deterioration of the Elk Lake water quality. The increase started between the 1950s and 1960s, while deterioration of the water quality wasn't officially noticed until the mid of the 1960's (see section 2.4.1; appendix A). If it had been monitored, the eutrophication might have been noticed in an earlier stage of development. Increasing diatom abundances (fig. 5.10) during the same period, especially for *Tabellaria sp.*, strengthen the above observations. This also underscores the use of diatoms as ecological indicators.

Unfortunately, the water quality data collected from government agencies that have been sampling Elk Lake during the past decades was not very useful in this first paleolimnological study of Elk Lake. In a follow-up study, the data can be analysed on a more detailed level.

Collected data on the historic events that happened in the Elk Lake watershed (see Appendix A) could hardly be used anywhere in this project. The earlier mentioned large-scale events that influenced the lake overshadowed all other. This is somewhat surprising considering the fact that even the construction and use of a highway was not recognizable in the analysed data set. A possible explanation is that the different water quality influencing events overlapped, and that additional statistical analysis of the data is necessary to extract the individual effects of each event from the data set.

7.3 Recommendations for future Elk Lake research

Of all the available paleolimnological methods and proxies, only diatoms were used where multi-proxy approaches are preferred. This would allow verification of inferred data, and could fill (some of) the gaps existing in the present knowledge of the water quality development of Elk Lake.

In addition to that, further analysis of the already collected data will clarify some of the still unresolved (research) questions. In a follow-up, diatom species abundances and water quality variables should be compared against existing lake training sets so the water quality in earlier periods can be inferred from diatom abundances in dated sediment samples.

With advanced statistical methods, the collected data could be further analysed for trends that were overlooked until now.

It is also advisable to verify the diatom data collected during this project, because there was no expert available for the counts and identification of diatoms present in the sediment core.

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Appendix A: Historic events in Elk Lake watershed

Year	End	Description
1858		Indian trail along east shore of Elk Lake, this presumably became East Saanich Road.
1873	1879	Foundation stone for the dam at the south end of adjacent Beaver Lake was laid. The water supply system (for the City of Victoria) was completed in 1879. By 1882, more than 1200 buildings were connected to the system.
1878	1879	Heavy snowfall.
1892		Construction of the railway started.
1894	1919	The Victoria & Sidney Railway. Operated for 25 years, with 1913 as peak year (carrying 123,599 passengers and 45,282 tons of freight). It ran along the west side of the lake (see map 3, CRD inventory, 1083). There was a passenger station, or water supply station located at Elk Lake.
1896		Construction of filter beds south of Beaver Lake, meant to improve water quality.
1910	1915	Major water expansion where the city of Victoria made the switch from Beaver-Elk Lake & Thetis Lake to the Sooke & Goldstream systems.
1912		People were able to walk out to the islands in Beaver Lake in the summer of 1912 (detail illustrating the effects of the water demands)
1914	1920	Elk / Beaver Lakes abandoned as city water supply source, but it remained in local use until 1920.
1916		Very heavy snowfall.
1923		Elk /Beaver Lake Park created.
1924		Mention of possible use first speedboat on Elk Lake.
1925	1950	First major enterprise focused on recreation was built: the Toby Jug, by Elderton Pease. An automobile camp was located directly across East Saanich Road
1939		Elk Lake Roller Skating Rink constructed.
1942		A pumping and filtering station was established to supply water to the Air Force Base at Patricia Bay.
1950		Very heavy and longlasting snowfall.
1951		First mention of new speed highway in Daily Colonist.
1953		Patricia Bay Highway constructed.
1960		Confirmation that diving float was constructed in Beaver Lake for the benefit of the public.
1960		New ferry service starts sailing between Swartz Bay & Tsawwassen - demands vast improvements to the PBH.
1961		Construction of a boat-launching ramp completed (winter works).
1962	1975	Wells augment the supply of water, decreasing the demand on Elk Lake.
1967		Elk Lake becomes part of the Greater Victoria's regional park system.
1967		Park maintenance.
1967		Chemical applications controlled the algae problems efficiently. Certain key areas were also treated for aquatic weed control with good results.
1967		One of the hottest summers in years!
1968		Winter works in the park: added parking, filling filter beds.
1969		Proposal: to remove seaplane dock and garage on the west side of the lake (just south of treatment plant) and to move boat ramp from north side to east side.
1969		Aquatic harvester used to keep weed problem under control.
1969		New dam at Beaver Lake is functioning well. It was possible to maintain running water in Colquitz Creek for the first time in many years this summer.

1972		Mention of trail around lake, and that it needs maintenance.
1977		The Greater Victoria Water District extends its pipeline to the north part of the peninsula, and Elk Lake (probably? See next entry) ceases to be used as a supply for water.
1979		Water supplies (from Elk Lake) were really discontinued
1987		One of the driest summers on record.
1993		Mention of geese population on Elk Lake is growing. Health risks?
1993		Resurfacing of Patricia Bay Highway from October 4, 1993.
1996		Repaving of part of Patricia Bay Highway.
2002		More than 50.000 vehicles use the Patricia Bay Highway on a daily basis. Plans for upgrading.

All this data was retrieved from the Saanich Community Archives, 2002.

Appendix B: Bathymetric map of Elk & Beaver Lakes

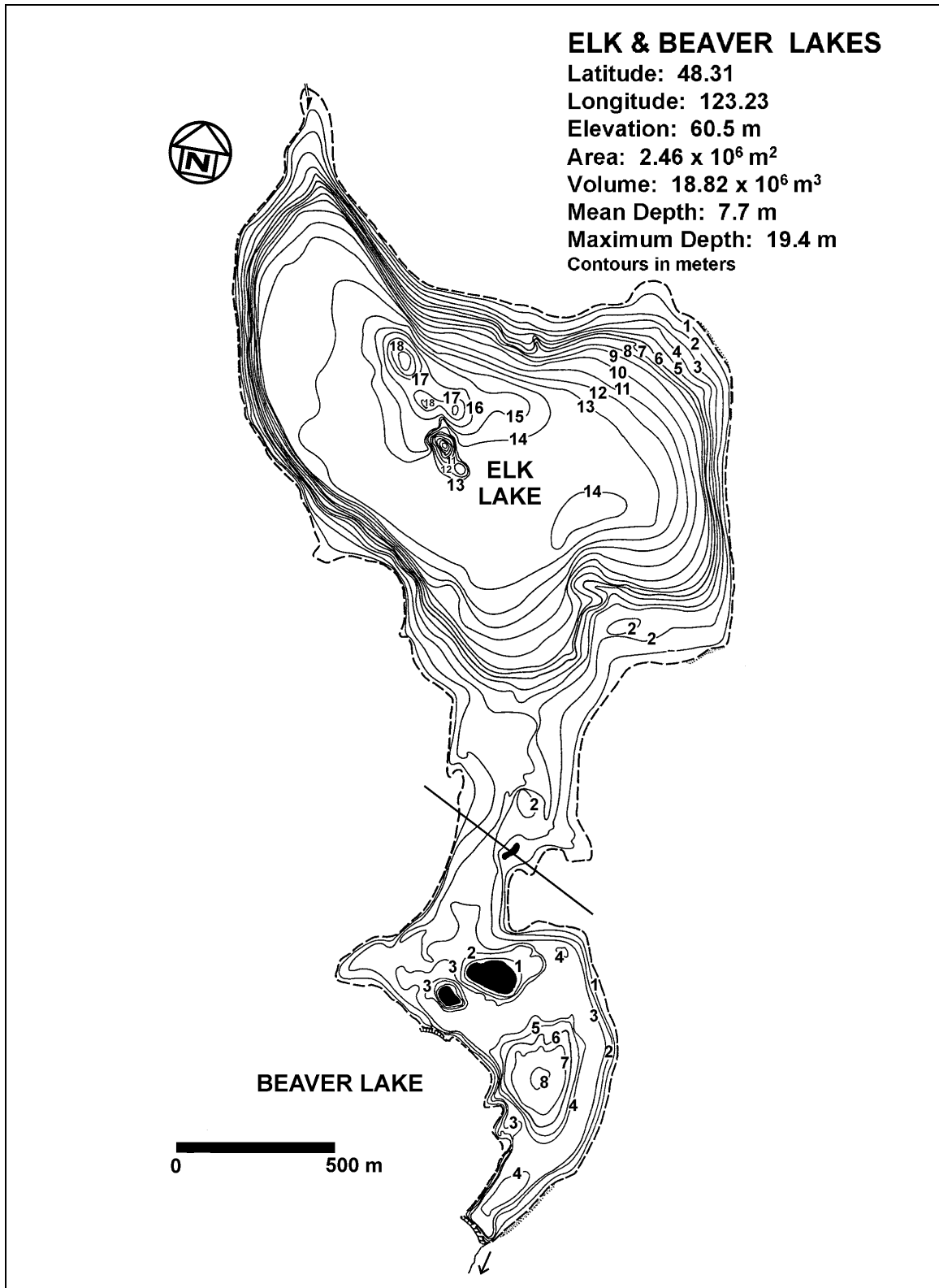


Figure C.1: Bathymetric map of Elk & Beaver Lakes (Spafard *et al.*, 2002).

Appendix C: Elk Lake Diatoms

Relative abundance of diatom genus/species at a certain moment in time.

Diatoms \ Year	1995	1993	1985	1976	1941	1868	1711	1671	1591	1511
Aulacoseira	17.4	16.6	13.7	21.7	20.9	27.5	49.1	63.6	59.4	68.5
Cocconeis	1.5	1.2	2.1	1.6	2.8	1.1	2.0	1.0	5.3	1.2
Cyclotella	5.3	2.7	7.0	6.1	5.3	5.6	11.8	5.0	4.3	7.3
Stephanodiscus	13.8	16.6	9.5	12.2	12.3	12.6	1.8	2.3	8.5	2.4
Tabellaria	17.2		16.2	5.3	3.1		0.5		0.9	0.5
T. flocculosa		9.4								
T. fenestrata		6.7				2.9				
<i>Fragilaria</i>										
F. (pseudo)construens	1.2	0.7	1.8	1.1	0.8		0.9	0.8	2.1	2.4
F. berlinensis						1.6				
F. brevistriata	2.7	13.6	2.4	3.7	7.5	7.5	6.6	4.5		2.4
F. capucina		1.7		0.5		0.3				
F. crotonensis	14.0	9.7	14.9	9.5	9.2	11.2	0.5	0.6	0.4	0.2
F. cyclosum	0.5									
F. Fasciculata cf.	1.0	0.5	0.3							
F. leptostauron	0.5		3.4	3.2	2.5	3.5	2.3	3.1	7.0	5.6
F. pinnata Ehrenb.				10.8	14.5	11.0	9.3	3.3		
F. virescens			0.9							
Fragilaria (other)	1.2	3.5	1.5	6.9	2.2	1.1	1.4	3.5	1.5	
<i>Achnanthes</i>										
Ach. joursacense		0.5			1.1	1.9	0.5			0.2
Achnanthes (other)		0.5		1.1	1.4				2.8	
Ach. / F. pinnata	17.4			8.2	9.7	6.1	7.7	6.6		
Ach pinnata		4.0	8.2							
F. pinnata		6.7	7.3							0.7
Amphora	0.2									
Asterionella formosa		0.2	2.1							
Cymatopleura solea		0.2								
Cymbella	1.2	0.5	0.6		0.6	0.8	0.5	0.8	1.7	0.2
Epithemia		0.5		0.3			0.2	0.6		0.2
Eunotia		0.2								0.2
Melosira			2.7							
Meridion			0.6						0.2	0.2
Navicula	1.7	1.0	1.8	2.6	0.8	2.1	1.4	0.8	1.9	
Naviculoid			2.1							
Neidium			0.6							
Nitzschia				0.5			1.1		0.4	
Pinnularia							0.2	0.8	0.4	
Rhopalodia						0.3				0.2
Stauroneis		0.2								
Surirella		0.5							0.2	

Unknown	3.1	2.0	0.6	4.8	5.3	2.9	2.5	2.5	3.0	7.1
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In 1996, K. Laird made an inventarisation of the diatoms present in the top layer of Elk Lake's sediment. The results are displayed below:

(Genus species)	(percentage)
Frag. crotonensis	32.17
Frag. pinnata	17.83
Aul. ambigua	13.18
Frag. construens	3.49
Fragilaria spp.	2.52
Steph. medius	2.33
Cyc. michiganiana	2.13
Cyc. stelligera (small form)	2.13
Steph. minutulus	1.74
Steph. niagarae	1.74
Asterionella formosa	1.55
Tab. flocculosa IIIp	1.55
Ach. minutissima	1.36
Aul. subarctica	1.36
Cyclosteph. cf. tholiformis	1.36
Navicula spp.	1.36
Frag. brevistriata	0.97
Frag. brevistriata var. inflata	0.97
Frag. capucina	0.97
Nav. minima	0.97
Ach. spp.	0.58
Aul. granulata var. angustissima	0.58
Cyclosteph. cf. invisitatus	0.58
Frag. construens f. binodis	0.58
Nav. cf. submuralis	0.58
Nit. spp.	0.58
Central area unknown	0.58
Ach. lanceolata var. dubia	0.39
Coc. placentula var. lineata	0.39
Cyclosteph. sp.	0.39
Cym. minuta	0.39
Nav. cryptocephala (KLB)	0.39
Nav. explanata	0.39
Nit. dissipata var. media	0.39
Ach. joursacense	0.19
Amp. pediculus	0.19
Coc. placentula var. euglypta	0.19
Frag. cyclopum	0.19
Nav. absoluta	0.19
Steph. parvus	0.19
Steph. cf. parvus	0.19
Steph. spp.	0.19
Total diatoms counted	516

Appendix D: Uses of modified Telmer gravity corer

The gravity corer used in this project was modified from a version used in the following work. There is currently no reference available specifically describing the corer.

Reports and Proceedings

- Kliza, D. and Telmer, K. (2001) Phase I. Lake sediment studies in the vicinity of the Horne smelter in Rouyn-Noranda, Quebec. GSC Open File D2952, CD-ROM.
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- Desjardins M., and Telmer K. (2002) Coupling sources of atmospheric lead and mercury inputs to lakes and implications for remobilization. American Society of Limnology and Oceanography (ASLO) 2002 Summer Meeting: Session SS3.17 Global Mercury Cycling from Natural and Anthropogenic Sources. Victoria, B.C.
- DesJardins M.J. and Telmer K. (2002) Coupling sources of atmospheric Pb and Hg inputs to lakes and implications for remobilization. Geological Association of Canada Annual Meeting, No. 282, Session: SY3 – Distribution of metals in the environment around smelters. Saskatoon. Saskatoon, Saskatchewan.

This information was made available by the designer of the modified corer, dr. K. Telmer.

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