Paleolimnological Elucidation of the Historical Water Quality of Sooke Reservoir, Victoria, British Columbia, by Diatom Stratigraphic Analysis

by

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B.A., University of Victoria, 1990
B.Ed., University of Victoria, 1992

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Biology

We accept this thesis as conforming
to the required standard

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Abstract

Following impoundment, reservoirs commonly undergo a rapid increase in planktonic primary productivity, known as "trophic upsurge," followed by a slower return to a more stable level of productivity. This upsurge is fueled by a pulse of nutrients, particularly phosphorus, derived from inundated soils and decomposing vegetation. This upsurge can be of concern in drinking water supplies where algal blooms may cause taste and odour problems. Sooke Reservoir, which supplies potable water to 80% of the population (312,500) in the Greater Victoria region, was created by damming the outflow of Sooke Lake in 1913 and raising the water level 3.7 m. The water level was subsequently raised 6.3 m in 1970 by the construction of a second dam. Future plans call for raising the water level an additional 6.3 m in 1998 but it is not known what effect this may have on the quality of water in the reservoir. Since neither historical phytoplankton nor water quality data are available, this paleolimnological study of sedimentary diatoms was undertaken to determine if changes in planktonic species composition or abundance, geochemistry or sedimentation rate, which occurred post-European settlement, were evident within Sooke Reservoir and could be attributed to changes in the watershed which have occurred in the past 125 years. An examination of the diatom microfossil record and geochemical and age profiles of deep water sediment were used to assess these changes and their relationship to known disturbances in the watershed, especially the effects of previous dam construction or other ecosystem perturbations.

Diatom fossils revealed that the composition and abundance of the phytoplankton community underwent a rapid change beginning in 1890. By the mid-1920's the evidence of this shift had disappeared. The onset of change in the phytoplankton community pre-dated reservoir construction and is thought to be a result of fish removal and altered trophic interactions. Other watershed disturbances including logging, road construction and fire have not resulted in significant changes in the phytoplankton community; however, the composition of this community has become increasingly variable over time. Increased variability may be a result of varying seasonal water levels and/or nutrient loading due to exposure of shoreline sediments as the reservoir is drawn down and refilled. Increasing the storage capacity of Sooke Reservoir may benefit the phytoplankton by reducing the magnitude of drawdown and stabilizing both water levels and nutrient inputs.

The sedimentation rate in Sooke Reservoir ranged between 1.1 and 1.7 mm/yr and was highest in the eighteenth century and lowest from 1898-1918. It has not increased as a result of recent watershed disturbance. Metal concentrations in the sediments were generally consistent with concentrations found in other Vancouver Island lakes.

Though the phytoplankton community of Sooke Reservoir is extremely sensitive to change in the short term, historically it demonstrated resilience and was able to integrate change and regain equilibrium within a few decades. What cannot be ascertained from this study is the threshold for alteration beyond which irreversible change will occur. This question must be addressed *in-situ* under present conditions. Raising the water level of the reservoir in the future may not have the same effect as it did in the past, because ecosystem response to disturbance is often non-linear. Caution must therefore be exercised when creating any disturbance within the watershed.

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Acknowledgements

Over the past two and a half years, many different people have contributed to this project. All of their contributions are very much appreciated:

Dr. Rick Nordin and Dr. Lou Hobson provided me with guidance and advice prior to, and throughout the course of this work. I extend my appreciation to them both, as well as to my committee members, Dr. Alan Austin and Dr. Chris Barnes. I would also like to thank Dr. Ian Walker for providing critical comment on my thesis and taking time out of his busy teaching schedule to act as my external examiner. Dr. Alan Austin also loaned me many taxonomic works and assisted me with diatom identifications.

Special mention must go to Rick Nordin who went above and beyond the call of duty by taking cores for me in cold January weather, helping me with field work, obtaining equipment, printing photographs, locating data and references and allowing me to make my own mistakes and learn from them.

Patrick Lucey encouraged me to begin this project. I thank him for motivating me, supporting me, carrying more than his share and knowing when to leave the country so I could finish on time.

Melissa McQuoid provided a much needed sounding board for methods and ideas; Bruce Jeffs spent many hours assisting with field work; Lesley Baldwin performed all the sediment core X-rays; Gordon Davies expertly manufactured custom equipment; Tim Lucey assisted with field work and with computer-aided information retrieval and graphics; David Vadnais and Shelley Bleakley assisted with many laboratory tasks; Chris Parks built field equipment and was never to busy to lend a hand; Laura Veary patiently located references; Frank Csitari provided encouragement and advice during the "afternoon shift" in Cunnigham's hallways; Emmanuel Hérique gave me a new perspective on diatoms; Frank Symes assisted with field and lab work; Katrina Moser provided many fire history references;

Michael Winkel helped me section cores in a moment of great frustration; Kevin Nickolichuk assisted with diatom identifications; Darcy Grant helped me in the lab and the field and made up one half of a great field team; Mr. H. Melville provided historical photographs of the Sooke Watershed including the earliest known photograph of Sooke Reservoir and Heather Down carefully reprinted them; Tom Gore explained photographic techniques and Dr. Chaman Singla assisted with electron microscopy. I would also like to take this opportunity thank the entire staff of Biology Stores and the Biology General Office for the many extra things they have done for me- it does not go unnoticed.

Russ Boyd and Doug Homer-Dixon provided priceless information on the history of the Sooke watershed, without which, this study would be incomplete; Stewart Irwin, Gordon Joyce and Sigi Gudavicius all provided essential data on Sooke Reservoir and the G.V.W.D. lands including photographs and maps.

Finally, I would like to thank my family for their love, support and patience in my pursuit of "professional student" status.

Funding for this project was provided by the Greater Victoria Water District and the Water Quality Branch of B.C. Environment.

Sooke Reservoir, looking north. October 28, 1914

Introduction

Overview

Numerous studies have compared the effect of impoundment and inundation on the trophic status of reservoirs with that of similarly-sized lakes (Ostrofsky, 1978; Ostrofsky and Duthie, 1980; Grimes *et al.*, 1984; Sebetich and Melcher, 1991). The reservoirs examined were most often created by damming rivers to form completely artificial impoundments (Campbell *et al.*, 1975; Elser and Kimmel, 1985; Melcher and Sebetich, 1990; Sebetich and Melcher 1991; Tundisi *et al.*, 1991). Relatively few reservoirs have been created from natural lakes. Those studied include Southern Indian Lake (Hecky, 1974, 1975; Hecky and Guildford, 1984; Hecky *et al.*, 1984; Newbury *et al.*, 1984; Planas and Hecky, 1984), Smallwood Reservoir (Duthie and Ostrofsky 1975; Ostrofsky 1978; Duthie, 1979) and the La Grande Complex (Schetagne and Roy, 1985). Though these reservoirs have been studied extensively, the limnological effect of lake to reservoir conversion is still poorly known. Even fewer studies have examined the trophic effect of turning a lake into a reservoir, and later raising the impounded water level.

Sooke Lake (hereafter referred to as Sooke Reservoir) is a drinking water reservoir on southern Vancouver Island, British Columbia, which supplies approximately 80% of the potable water consumed in Greater Victoria (Figure 1). The reservoir was created in 1913 by damming the Sooke River downstream of the outlet of Sooke Lake (Figure 2). This dam raised the lake level 3.7 m and flooded 63.7 ha of land. The impounded water level was then raised 6.5 m in 1970 by the construction of a larger dam, flooding 171.2 ha of surrounding lands. The Greater Victoria Water District plans to raise the water level of Sooke Reservoir a third time (6.3 m) during the next decade in order to meet the assessed storage needs of a projected increase in population on southern Vancouver Island. This will flood 143.5 ha of land and increase the surface area of the reservoir to 750.6 ha, over double the original surface area of Sooke Lake. It is not known what effect this increase in surface elevation may have on the quality of the water in the reservoir.

Following impoundment, a commonly observed phenomenon in reservoirs is an abrupt trophic upsurge followed by a slower return to a lower, stable productivity level (Ostrofsky and Duthie, 1980). This upsurge refers to an increase in primary production following a pulse in those variables to which the upsurge is directly or indirectly related. Often this increase is attributed to the inundation of land surrounding the reservoir from which large quantities of organic carbon and nutrients (primarily phosphorus) are made available to aquatic food webs (Ostrofsky, 1978; Grimard and Jones, 1982). The upsurge can last for a few months or for several years depending upon the flushing rate of the reservoir. Following this upsurge, a trophic depression is often evident due to a reduction in nutrient and organic detrital inputs and a cessation of aquatic habitat expansion (Schallenberg, 1993). As nutrient input and flushing rates stabilize, the system reaches a new equilibrium.

The timing and magnitude of change differs between system constituents. In the LaGrande Reservoir complex in Quebec, Schallenberg (1993) found that water colour, total organic carbon (TOC), the carbon to nitrogen ratio (C:N) in the water , total phosphorus, and turbidity reached their maximum perturbation (relative to pre-impoundment levels) in the first year after impoundment. Chlorophyll *a* and silica values did not peak until the second year; total nitrogen and iron peaked in year three and conductivity reached its maximum during the fourth year. Of these variables, silica showed the smallest increase (50% above background) while the C:N ratio increased 250% (x 2.5) and phosphorus levels doubled (x 2.0).

In the long term, perhaps the single greatest difference between lakes and reservoirs is the alteration of the natural timing of water movement imposed by the manipulation of reservoir water levels. Since the primary function of a reservoir is to capture and store water, water which would normally flow through a lake during periods of high runoff (and consequent high turbidity) is retained within the reservoir until the reservoir refills. During periods of low flow, water is actively withdrawn from the reservoir, exposing shoreline sediments to erosion and subsequent re-inundation as the reservoir is more rapidly refilled during the next rainy season (Hecky and McCullough, 1984). Laboratory studies have indicated that drought-induced (exposed) sediment dehydration may be followed by a significant increase in internal phosphorus loading under both aerobic and anaerobic conditions (Fabre, 1988; Ostrofsky and McGee, 1991; Qiu and McComb, 1994). Fabre and Patau-Albertini (1986) have shown that sediments within a reservoir are distributed heterogenously and that the phosphorus content of the sediments is dependent upon the duration of exposure during drawdown (1986). The act of constructing and operating a reservoir thus creates a waterbody which behaves differently than a lake. Present knowledge of the subject does not allow precise prediction of what the effect of impoundment would be on an existing lake, nor to what extent inundation of surrounding lands can occur before significant trophic effects are discernable. Both effects have significant implications for reservoir management.

One means of assessing the likely future limnological impact of raising the dam, is to examine the response of the phytoplankton community following previous dam construction projects; however, few water quality or phytoplankton data were collected for Sooke Reservoir until the late 1980's (Lang and Austin, 1984). In cases such as this, when little or no historical information is available, paleolimnological techniques can be used to reconstruct the waterbody's water quality history or to examine past changes in lake biota.

With few exceptions, such as Lake Windermere, Lake Mendota and Lake Washington, very few long term limnological data sets exist (Edmondson, 1991; Maberly *et al.*, 1994). In order to assess the causes, magnitude and timing of perturbation, and thus predict possible future impacts, some knowledge of the pre-disturbance condition of the lake is necessary (Fritz *et al.*, 1993a). Paleolimnological techniques can provide information on nutrient enrichment (Anderson *et al.*, 1990), land disturbance (Merilainen *et al.*, 1982; Sly, 1991), precipitation events (Edmondson, 1991), water chemistry (Cumming *et al.*, 1995), watershed fire history (Bradbury, 1986) and sedimentation rate (Evans and Rigler, 1980). In particular, the assemblages of diatoms preserved in lake sediments can directly reflect the phytoplanktonic composition and productivity of lake diatom communities, and can indirectly reflect lake water quality including pH (Flower *et al.*, 1983; Charles, 1984, 1985), alkalinity (Fritz *et al.*, 1993b), nutrient status (Battarbee, 1986), metal concentrations (Dixit *et al.*, 1992) and salinity (Cumming *et al.*, 1995). Diatoms are particularly good paleoecological indicators of water quality due to their ubiquitous nature and due to the fact that they continuously integrate changes over time (Stockner, 1971). Their siliceous frustules preserve well in most sediments. The size, shape and sculpturing of their valves is taxon-specific and the ecological requirements and preferences of many species is well described (Patrick, 1963; Patrick and Reimer, 1966; Lowe, 1974; Cumming *et al.*, 1995). Since diatoms dominate the phytoplankton in most oligotrophic Vancouver Island lakes (Brown, 1979) they are a logical choice for the paleolimnological investigation of Sooke Reservoir.

Diatom indices

Diatoms (Class Bacillariophyceae) are divided into two orders based upon the shape of their frustule in valve view: round (Order Centrales) and elongate or pennate diatoms (Order Pennales). The Pennales are further subdivided into "tribes" on the basis of raphe number and location, and morphology of the frustule: Araphidineae (A), Biraphidineae (B), Monoraphidineae (M) and Raphidioidineae (R). Both the Centrales and Araphidineae consist chiefly of planktonic species, while the B, M and R tribes are primarily benthic. The benthic forms inhabit both streams and the littoral zone of lakes, where they live on rocks, sand, mud, aquatic macrophytes or other suitable substrates. The abundance of littoral forms in deepwater sediment, in relation to planktonic species, is primarily a reflection of the extent of littoral development and thus of lake morphometry (Stockner, 1971).

In 1967, Stockner and Benson proposed a lake classification scheme based upon the ratio of Araphidineae to Centrales species in deepwater sediments. It was based upon the observation that a major shift in planktonic diatom abundance, from Centrales to araphidinate species, occurs in temperate lakes which exhibit accelerated eutrophication (Stockner, 1971). Lakes with an A:C ratio of 0–1.0 are considered oligotrophic, 1.0–2.0 mesotrophic and >2.0 eutrophic. Though this classification scheme does not accurately predict trophic status in eastern North American lakes (Brugam, 1979; Battarbee, 1986), it is effective when used on west coast lakes, in part because west coast data sets were included during its formulation. Several of the species used in the formulation of this index are dominant in the sediments of Sooke Reservoir: *Cyclotella stelligera, Cyclotella ocellata, Stephanodiscus astraea, Asterionella formosa* and *Tabellaria fenestrata.*; therefore, it may be expected to accurately predict trophic changes in Sooke Reservoir. If the index does hold true for Sooke Reservoir, one would expect an increase in the A:C ratio as a result of increased nutrient input during impoundment and increased shoreline erosion (increased shoreline length to lake surface area ratio).

Objective

The objective of this study was to determine if changes in planktonic species composition or abundance, geochemistry or sedimentation rate, which occurred during post-European settlement, are evident within Sooke Reservoir. An examination of the diatom microfossil record, geochemical profiles and age profile of deep water sediment cores were used to assess these changes and to examine their relationship to known disturbances in the watershed and in the lake, especially the effects of construction of the two previous dams.

Study Area

Sooke Reservoir is located at 48° 33'N lat. and 123° 42'W long. on southern Vancouver Island, British Columbia. It has a catchment area of 7070 ha, including the reservoir surface area of 607.1 ha at an elevation of 180.7 m a.s.l. (above sea level) (Axys, 1994; Hugh Hamilton Ltd., 1994) (Table 1). It is 7.2 km long with a maximum width of 1.47 km (north basin; 1.1 km at the widest point in the south basin) and a main axis running NNE (Lucey, 1994). Its oligotrophic waters exhibit very low turbidity and moderate true colour values (Table 2; Ayxs, 1994) and a have a Secchi Disk depth of 6-10 metres (Lang and Austin, 1984). It is a temperate monomictic lake– a spring thermocline typically develops during April and May and stabilizes at a depth of 12-20 metres during August and September (Lucey, 1994). Fall and winter storms cause the waters to be vertically well mixed with no thermal stratification between November and April. Winter ice cover is rare due to the mild west coast climate.

The reservoir presently occupies 8.6 % of the total watershed area (at full capacity). This is a substantial (62%) increase over the original lake area of 5.3% of the total watershed area. Between 1913 and 1970 this value was 6.2 %. If plans to raise the reservoir level in 1998 proceed, the reservoir will occupy 10.6 % of the total watershed area (Table 3).

Physical Features

Sooke Reservoir lies within the Insular and Coastal Mountain Limnological region of south-eastern Vancouver Island (Northcote and Larkin, 1966). The gently rolling terrain is typical of the Nanaimo Lowland Region. The northeast portion of the watershed consists of well-rounded and hummocky hills with minor bluffs and cliffs. Eighty-five percent of the Sooke watershed has a slope between 0 and 30% while less than five percent has a slope of 46% or greater (Terrasol, 1992). This high percentage of gentle terrain means that, in general, the slope stability is good in its undisturbed condition, and the risk of erosion and sediment input to the reservoir is minimal.

Climate

The region is within the rain shadow of the Olympic Mountains and is subjected to the moderating influence of the North Pacific Drift (which warms coastal air masses), producing year round mild temperatures (Terrasol, 1992). Precipitation is light, with approximately 70% of the annual total received between October and April in the form of rainfall (Figure 3). Snowfalls are intermittent and heavy snowpacks are therefore uncommon.

Precipitation within the Sooke Reservoir watershed is measured at an Environment Canada climatological station located 1.5 km from the northern end of the reservoir (48°34′N, 123°9′ W). This station (elevation 231 m) has recorded monthly precipitation continuously since 1966. Mean annual precipitation at this station is 1,465 mm. A second station on Sooke dam, at the southernmost edge of the reservoir, has been operated by the GVWD since 1913. From 1895 to 1913 precipitation measurements were made at

Goldstream dam, 6.5 km to the southeast. GVWD data show a mean annual precipitation of 1,658 mm (13% greater than values recorded at the northern end). By comparison, Shawnigan Lake, 10 km to the north, receives 1,226 mm per year and Victoria International Airport receives 858 mm. During the last century, the year with the lowest annual precipitation was 1943/44 (1033.8 mm) and the highest annual value was recorded in 1967/68 (2711 mm).

Vegetation

The principal sub-catchment basins supplying Sooke Reservoir lie within the Very Dry Maritime subzone of the Coastal Western Hemlock Biogeoclimatic zone (CWHxm)(Meidinger and Pojar, 1991). This zone occupies elevations from sea level to 900-1050 m a.s.l. and is characterized by Western Hemlock stands interspersed with Coastal Douglas Fir and Western Red Cedar. In southern drier regions, such as the Sooke watershed, Douglas Fir is more abundant. The region is characterized by a cool mesothermal climate: cool summers and mild winters. Mean annual precipitation in the Very Dry Maritime subzone is 1505 mm and the mean annual temperature in this zone is 9.3°C. Key floristic features of this zone include: a) the prominence of Western Hemlock, b) the sparse herb layer and c) the predominance of several moss species, especially step moss (*Hylocomium splendens*), lanky moss (*Rhytidiadelphus loreus*) and Oregon beaked moss (*Kindbergia oregana*) in drier areas. Much of the Sooke Watershed is characterized by a Douglas Fir-Western Hemlock-Salal complex which has nutrient-poor to medium soils. A water deficit in the growing season and severe nitrogen deficiency are common.

Numerous ecosystem types can be found within the CWH zone including salal-lichen complexes on exposed rock; well-drained areas dominated by Douglas Fir (*Pseudotsuga menziesii*), Arbutus (*Arbutus menziesii*) and Red cedars (*Thuja plicata*); and low lying wetlands comprised of willow (*Salix* spp.), skunk cabbage (*Lysichiton americanum*), *Spirea* spp., sedges (*Carex* spp.) and grasses (Meidinger and Pojar, 1991). Other tree species include Lodgepole pine (*Pinus contorta var. latifolia*), Western white pine (*Pinus monticola*), Grand fir (*Abies grandis*), Red alder (*Alnus rubra*), Broadleaf maple (*Acer macrophyllum*) and Black cottonwood (*Populus balsamifera ssp. trichocarpa*). Salal (*Gaultheria shallon*), Oregon grape

(*Mahonia oregonensis*) step moss (*Hylocomium splendens*), Sword Fern (*Polystichum muntinum*) and bracken (*Pteridium aquilinum*) are dominant species throughout the watershed (Hugh Hamilton Ltd., 1994). A small area west of Rithet Creek is classified as Moist Maritime Subzone (CWHmm) and is characterized by higher mean annual precipitation (2124 mm), lower mean annual temperature (5.5 °C) and different vegetation including the presence of Amabilis Fir (*Abies amabilis*), blueberry (*Vaccinium spp.*) and bunchberry (*Cornus canadensis*) species and the absence of the ferns and blackberries. Table 4 summarizes the biogeoclimatic classification of this region. Fire, windthrow, timber harvesting and disease are the dominant processes affecting soil moisture and surficial material depth in the Sooke watershed and result in strongly differentiated vegetation in all areas (Terrasol, 1992).

Geology

The Devonian and Carboniferous bedrock of the Sooke watershed is principally comprised of Metchosin volcanic materials which include basalt flows, tuffs and agglomerates. This parent material has subsequently been deformed by intrusions of batholitic diorite, Saanich granodiorite and quartz diorite, and Sicker porphyrites. The northern edge of the watershed is underlain by conglomerate, sandstone and shale referred to as the Cowichan Group (Lucey, 1994).

The surficial materials of the watershed were deposited approximately 10-20,000 years ago during the Fraser Glaciation. These deposits are shallow and discontinuous, interspersed with deeper till blankets and exposed bedrock. Those materials deposited post-glaciation include colluvium on steeper slopes and fluvial material deposited by streams such as the alluvial fan created at the mouth of Rithet Creek (Terrasol, 1992). Marshes, bogs and fens have developed in low lying areas next to lakes which are susceptible to ponding and flooding.

The till-derived soils of the watershed are gravelly–sandy loam in texture. Upper elevations are dominated by Ferro Humic Podzols, while Dystric Brunisols are found at lower elevations. The Podzols are rich in silica, but poor in magnesium and calcium carbonate, and thus are very poorly buffered. The accumulation of organic matter plus iron and aluminum is typical of Ferro-Humic Podzols that form under humid west coast forest conditions. The Brunisols are relatively undeveloped from the parent material and contain high percentages of relatively inert gravel and quartz sand. Dystric Brunisols have a pH less than 5.5 (Valentine *et al.*, 1978). Because both of these soil types contain a limited pool of nutrients, ecosystem productivity must be maintained by their efficient cycling. The overall effect of the geology on water quality is to yield a year-round water supply which is slightly acidic (pH 6.0 to 7.0) and nutrient poor; these waters have a hardness value ($CaCO_3$) which ranges between 14 and 25 mg/L.

Hydrology

The Sooke Reservoir watershed includes eighteen creeks or streams with total sub-basin areas greater than 3 hectares (Figure 4). Of these streams, only eight contribute significant quantities of water (Table 5). Staff gauges were installed on Rithet and Judge creeks in the fall of 1993; however, no flow data are available for the other streams and relative contributions of water to Sooke Reservoir must be estimated from catchment area only. In order of decreasing watershed area they are: Rithet Creek, Judge Creek, Whiskey Creek, Horton Creek, Begbie Creek, "Stream #18", Stream 17S and "Stream #16" (Axys, 1994). The hydrography of these streams is typically coastal. Fall rains begin in October and continue until April, and constitute approximately 70% of the total annual precipitation (Figure 5).

Water is actively withdrawn from the reservoir year-round. Outflow consistently exceeds inflow between May and October (Figure 6). In dry years this water deficit can occur as early as March and can continue into November. Maximum withdrawal occurs during the drier summer months of June-August (Figure 7). Water is also released from Sooke Reservoir to supply Charters Reservoir and provide adequate flow to sustain the fish in the Goldstream and Sooke Rivers. This volume has been recorded only since 1992, therefore outflow volumes recorded prior to this date are underestimates.

Water residence time, as calculated for the years 1985-1994, varies between 2.3 and 1.9 years. These values are consistent with estimates of a mean retention time of 18 months (between 1951 and 1988) made by Dayton and Knight (1994). The lower values result from the more complete outflow data available since 1992 and more accurately reflect actual residence time (mean 2.0 years, n=3). Unlike a lake, flushing does not occur immediately once inflow exceeds outflow since the reservoir must first refill. Sooke Reservoir typically tops the spillway between March and April; however, following years of low precipitation and high water usage the reservoir does not spill (Greater Victoria Water District, 1994).

The trophic state of a lake or reservoir is largely determined by the concentration of phosphorus in its waters. In its simplest form, the annual change in the P content of a lake is related to the P concentration of inflowing waters, P losses to outflowing waters and P deposition to lake sediments. The net fraction of inflowing P deposited on the sediments is termed the sedimentation coefficient. Based upon the water residence times given above, the mean sedimentation coefficient for Sooke Reservoir ($1/(1+\sqrt{\rho})$ where ρ= flushing rate) between 1985 and 1994 is 0.58 (Larsen and Mercier, 1976).

Suspended sediment enters the reservoir from inflowing creeks and shoreline erosion. Reservoir bathymetry suggests that only Rithet, Judge, Whiskey, Horton, Begbie and "#18" Creek contribute sediment to the North Basin; however, little is known about the physical limnology and mixing characteristics of the reservoir so predictions of relative sediment and nutrient inputs to the North Basin are speculative.

Limnology and Fisheries

Little historical information exists on either the limnological or fisheries aspects of Sooke Reservoir. Records containing those few data which have been located are included in Appendix A. These include an analysis of uncertain date (but believed to be post 1925 as it includes Goldstream Water Works data) from the City of Victoria Archives. Various forms of nitrogen were tested including nitrate. The nitrate concentration recorded was 0.68 mg/L, however the accuracy of this value is questionable. Of note is that "microscopical examination of these waters revealed extremely small amounts of fine siliceous matter. In such insignificant amounts, this cannot be regarded as objectionable in the least. Bacteriological analyses show the water to be free from pathogenic bacteria." The "siliceous matter" is most probably diatoms since chrysophytes would likely have imparted an odour to the water which would have been "objectionable". No mention is made of other larger, more readily identifiable algae such as chlorophytes or cyanobacteria.

A second, chemical, analysis was conducted on July 12, 1949 by J.F.J. Thomas of the Canada Department of Mines and Technical Surveys, Mines Branch, Industrial Minerals Division (Thomas, 1953). It covered 26 parameters including nitrate, sodium, potassium, silica, colour, turbidity, pH and temperature. No phosphorus measurements were made. The nitrate value is recorded as zero, although the sample was stored for 12 days prior to analysis, making the result highly suspect in any case. The specific conductance of 57.5 µmhos is much higher than present day values (median 44.2 µmhos/cm between Apr. 1990-June 1993) (Table 2) (Axys, 1994), suggesting that a) general ion concentrations may not have increased significantly since 1949, b) the samples were taken at different locations or in different seasons or c) lab analysis was in error.

A lake survey was conducted by the provincial government in 1959 (Field notes read May 16, 1958, typed notes read May 17, 1958, May 15, 1959) (Balkwill, 1991). No water chemistry was taken, however a temperature profile and depth area data (hypsographic curve) were collected. A fisheries census conducted by gillnet at the same time captured 7 immature Cutthroat Trout (*Salmo clarkii* Richardson) ranging in size from 4 to 10 oz. and from 9.25 to 10.75" in length. Eight immature Dolly Varden (*Salvelinus malma* (Walbaum)) (1-5 oz, 4.25- 8.75") and 1 immature Kokanee (*Oncorhynchus nerka* (Walbaum)) (4 oz., 8.5" long) were also obtained. Though no specimens are recorded on the log sheet, Prickly Sculpin (*Cottus asper* Richardson) is checked on the checklist of species found in the reservoir. Plankton samples were taken but no indication is given as to the species composition or abundance.

A major canyon and waterfall is located approximately 13 km downstream of the Sooke Reservoir and which prevents the passage of anadromous fish, so their absence from the reservoir in 1959 is not surprising. A second aquatics inventory undertaken by the Assessment and Planning Division of the B.C. Ministry of Environment in 1980, confirms that Cutthroat trout are the only fish species with widespread natural distribution above the Sooke River Falls; however, juvenile Coho salmon were found immediately upstream of the falls where they had been planted from the Maryvine Creek incubation box (Pendray, 1980).

Zooplankton and Phytoplankton

A zooplankton survey of Sooke Reservoir was conducted in 1991 by members of the Department of Biology at the University of Victoria (Gordon and Littlepage, 1991). Taxa were identified from 25 plankton samples collected between July 9, 1990 and September 30, 1991. Overall, rotifers were found to be numerically dominant (70- 80% of the total individuals counted), followed by cladocerans, predominantly *Daphnia* spp. (8-12%), calanoid copepods (7-11%), predominantly *Hesperodiaptomus franciscanus* and *Leptodiaptomus tyrrelli*, and cyclopoid copepods (5-7%), predominantly *Diacyclops biscuspidatus thomasi*. Other species identified from these samples included: *Bosmina longirostris* (O.F.M.), *Diaphanosoma* sp., *Ceriodaphnia?*, *Holopedium gibberum* Zaddach, *Leptodoptera kindti* (Focke), *Eurycerus sp.*, *Alona quadrangularis* (O.F.M.), *Polyphemus pediculus* (L.), *Sida crystallina* (O.F.M.), *Microcyclops varicans rubellus*, *Tropocyclops prasinus* (Fischer), *Eucyclops speratus* (Lillj), *Epischura nevadensis* Lillj, *Osphranticum labronectum* Forbes, *Kellicotia longispina*, *Kerratella cochlearis?*. The presence of an unknown Chironomid species was also noted.

Phytoplankton samples were collected from Sooke Reservoir intermittently between 1967 and 1989 by the University of Victoria (Lucey *et al*, 1984; Linger *et al.*, 1994). Since 1989, samples have been collected on a more regular basis by the G.V.W.D., though data are largely uninterpreted. Sooke Reservoir is dominated by diatoms throughout most of the year, in particular, by *Cyclotella* spp., *Melosira (Aulacoseira)* spp. and *Asterionella formosa*. Beginning in May, diatom abundance decreases while Chrysophyte and Cyanophyte populations increase. The Chrysophyte group is dominated by *Dinobryon* spp., usually by *D. bavaricum* and/or D. *cylindricum* and later by *D. divergens*. *Aphanocapsa* spp. are the dominant Cyanophytes. Of note, is that *Melosira (Aulacoseira) distans* usually maintains its numerical dominance during this period. By July, Cyanophytes may dominate the phytoplankton and include *Gloeotrichia* spp. and *Gomphosphaeria* spp. in addition to the *Aphanocapsa* spp. In the autumn, the phytoplankton community is once again diatom dominated though *Dinobryon* spp. and a few Chlorophyte species may also persist. Overall abundance of phytoplankton decreases throughout the winter and increases again with increased light in the spring (Lucey *et al*, 1984; Linger *et al.*, 1994).

History of the Sooke Watershed

This study was necessitated by a lack of historical water quality data on Sooke Reservoir. Information on events which may have influenced the quality of water in the reservoir is rapidly disappearing as photographs and records decay, and those who can recall these events die. Though not always directly relevant to the water quality history, names, dates, and similar details of the region's history are provided here as material for future reference should further information be necessary. Significant events and dates are summarized in Table 6. This information has been gleaned from archival documents, both provincial and city, newspaper features and anecdotal information provided by Mr. Doug Homer-Dixon, (an employee and later chief forester of the Greater Victoria Water District between 1950 and 1991). Mr. Russ Boyd, currently Operations Superintendent (Watershed Management Department) for the G.V.W.D. has been most helpful in locating information, filling in gaps in history and providing modern or commonly used site names for historical locations. This history is divided into two parts for ease of explanation: watershed history and water supply history.

Background

In comparison to Eastern North America, European settlement of Vancouver Island is a recent event. Approximately 150 years ago, in 1843, James Douglas arrived with 15 employees of the Hudson's Bay Company on the paddle wheeler "Beaver" to establish a fort on southern Vancouver Island. The area was reported to have a safe harbour, timber and fertile plains but no freshwater stream (Hall, 1989). This settlement was named Camosun and later changed to Fort Victoria. By the year 1858, the population had not yet reached 500 people. The City of Victoria was incorporated in 1862 and two years later a goldrush began on the Leech River, south and west of Sooke Lake (Figure 1). Vancouver Island and the adjacent mainland territory were made a Province of the Dominion of Canada in 1871, with Victoria as the capital.

Sooke Watershed History

The first known settlement within the Sooke watershed was the Healy farm on the site now occupied by Deception Reservoir. This land was originally quite swampy and approximately 15-20 acres were drained through a ditch hand-dug by the owner. Mr. Healy (after whom Mt. Healy was named) raised beef cattle on this site to feed the gold miners working at Leechtown during the goldrush of 1864-1866.

At the start of the goldrush, the only access to Leechtown was via government trail (built in 1861) up the Sooke River (BC archives; Hall, 1989). The road from Victoria to Leechtown was not constructed until 1865. Approximately ten years later, increased settlement in the Cowichan Valley, 60 km north of Leechtown, prompted the colonial government to construct a trail linking Cobble Hill to Leechtown and thus to Victoria. The trail followed the shorelines of Sooke Lake and Shawnigan Lakes. Public pressure forced the government to upgrade the trail to a wagon road in 1884. The journey was a long one– taking three days from Cobble Hill to Victoria, over rough ground, steep grades and numerous switchbacks (MacFarlane, 1995). As a result, a number of roadhouses were constructed for travellers to rest and eat. The first one was the Goldstream Hotel located at the present site of Ma Miller's Pub (2903 Sooke Lake Road). The second stop was a log house at Cabin Pond. The farm at the Sooke Lake Narrows (called the Daisy Patch) served as the third rest stop (Figure 8) and the fourth was at Shawnigan Lake. By the early 1880's an entrepreneur named William Healey purchased 138.8 ha (343 acres) of property on Sooke Lake and set up a fishing camp, presumably to take advantage of the traffic on the new road. It is not known whether this was the same Mr. Healey (Healy) who owned the farm at the south end of the lake or where the fishing camp was situated. The prize catches were 1.25 kg (2 3/4 lb.) cutthroat trout (Hall, 1989). Healey's property was expropriated in 1912 and the camp closed.

The coming of the E & N railroad in 1888 made travel up and down Vancouver Island much easier and eliminated the need for the roadhouses. It also firmly established Shawnigan Lake as the preferred summer resort since the railway bypassed Sooke Lake via the adjacent Niagara watershed (Baird, 1985). The east point of Sooke Lake (adjacent to the Daisy Patch) had already been subdivided at this time, though no summer homes were ever built because the land was soon acquired by the city as part of the water supply area. The main house located at the Daisy Patch site was rafted to the south end of Sooke Lake and used as a caretaker's house when the first dam was constructed in 1913 (Homer-Dixon, pers. comm., 1995). The Malahat Highway was opened in 1911, further reducing the traffic through the Sooke watershed (MacFarlane, 1995).

The City of Victoria acquired the Sooke watershed lands for the purpose of supplying drinking water in 1911 (see following section for details). Gravel from the north end of the reservoir was moved via a short narrow gauge railway to barges on the water which carried the gravel to the dam site at the south end. This was the first recorded activity of an "industrial" nature in the Sooke watershed.

Construction of the Canadian Northern Pacific Railway (later the Canadian National Railway) began in 1911. The route was intended to compete with the Canadian Pacific Railway for the lucrative oriental silk market. Construction proceeded slowly. By 1916, the wartime demand for Sitka spruce to build aircraft was high. The federal government provided funding to build 70 miles of line, but the war ended before it could be built.

The Canadian Northern line began in Victoria at the Point Ellice Station. It ran west to Colwood, Metchosin and Rocky Point before turning north along the Sooke River to Leechtown and the east side of Sooke Lake. From there it continued north along the east shore of Shawnigan Lake to Deerholme and Mill Bay. The line reached Lake Cowichan in the fall of 1923 and an extension to Youbou was completed in 1925. The track to Nitnat (formerly Kissinger) at the north end of Lake Cowichan was added in 1928. A spur line between Victoria and Sidney was constructed between 1915 and 1917, however passenger service was discontinued on July 6, 1921. The line was formally closed in 1935 (Baird, 1985).

The arrival of the Canadian Northern railway created new opportunity for industry in the Sooke watershed. In 1919, W.G. Dickenson, of Victoria, opened a talc quarry on [Old] Wolf Creek (Old Wolf Creek drains Old Wolf Lake and enters the Sooke River south of the reservoir). The talc was transported to Sidney by rail where it was crushed (Baird, 1985). In the 1920's the Kapoor Logging Company began logging the Goldstream watershed. The town of Kapoor, (which no longer exists) which included a sawmill, was established at the present site of the north entrance of the Kapoor tunnel at the south end of Sooke Reservoir. The logging progressed at a very rapid pace- approximately 2000-2500 ha of the Goldstream watershed were logged in only 15 years (Homer-Dixon, pers. comm., 1995).

During the 1929-1939 Depression a "relief camp" was built at the south end of Sooke Reservoir (site is underneath the present (1970) dam). The camp housed 30-50 men whose job it was to build a road from the south end of the dam to the present intersection of 23S and Sooke Lake Main. They surveyed the road right up to the Rithet Valley but did not complete it due to the outbreak of war. This "tote road" was cleared by hand and the timber cut into four foot lengths. The wood was then used to heat greenhouses in Victoria (located along Shelbourne St. and at the foot of St. Charles Street) which supplied produce for the City of Victoria. Firewood was also supplied from the Langford and Colwood area by the Ridley family. Piles of firewood were still visible along the tote road until the 1950's (Homer-Dixon, pers. comm., 1995).

Logging activity within the Sooke watershed did not begin until 1951. A contract was let at this time to log a small area at the north end of Sooke Reservoir. (It appears as an inverted "L" in the Northeast portion of the watershed. North and west of this area, a small area, 600 m wide (30 chains), juts out to the north- it was the second contract (first logged by the uncle of Russ Boyd)). In 1957, the GVWD began construction of a road from highway 117 around the north end of the reservoir to the west side (Figure 9). The road, Sooke Lake Main, continued down the west side reaching the south end of the reservoir in 1961. The original 1930's survey maps, made by the relief camp workers, were used to lay out the route. Spur roads were then built, as needed, to access timber. The first area logged was 3S, in 1957. Crews then proceeded in 1957/58 to the area north of the shop and to 11S (up from the main road on the right). Rithet Creek Bridge was built in 1959. The west side of the Rithet valley was logged first, in 1960/61. Logging on the east side continued until the mid 1970's (Homer-Dixon, pers. comm., 1995).

Rithet Creek is the only year round inflow source of surface water for Sooke Lake. Prior to any logging in the Rithet Valley and prior to the construction of the 1970 dam, a delta, of approximately 2 ha, extended from the mouth of the creek into the reservoir. These rich soils were excavated and used to cover the area surrounding the dam spillway during construction of the second dam in 1970. Anecdotal information indicates that, following heavy rainstorms, a sediment plume often extended halfway across the reservoir. This plume flowed northward due to the prevailing southerly winds and constriction of water flow between the north and south basins (precipitation is usually from southwest winds). In 1970, a channel 1 m deep, was hand-dug in the reservoir bed between the north and south basins to increase water flow from the north to the south basin. Before the fall rains could fill the newly enlarged reservoir in 1970, only three usable feet of water were left in the south basin. Severe water restrictions were put in place, so that water could be diverted to the Goldstream River for the fall salmon migration. Plans were put in place to pump water from the north to the south basin, should it become necessary. The needed rain arrived and water topped the spillway of the new dam on February 4, 1970 (Homer-Dixon, pers. comm., 1995).

Clearing for the construction of the second dam was begun 1968. It took three years to clear the necessary 182 ha (450 acres) of shoreline. Debris was piled in 45-50 piles along the shore with loaders (18 m grapple) and burned. Small pieces of debris were picked up by hand to prevent clogging of the water intake screens. Trash booms were placed across the reservoir next to the dam, at the narrows and in the north basin. The water level was raised an additional 6.5 m to provide 10.7 m of water in the south basin. At the same time, the Council Creek diversion was constructed and highway 117 was relocated up the hillside to its present location between the old roadway and the CN right-of way. One of the last times the CN line was used, was in the fall of 1977, when the world's tallest flag pole was cut near the headwaters of Rithet Creek and taken out of the watershed by rail. The Koksilah trestle was too weak to carry a full sized locomotive, so a yard locomotive with three flat cars was used to carry the tree. The tree travelled across the country by rail to Toronto where it stands as the world's tallest (unsupported?) flagpole in the CNE stadium. The entire journey was documented on film (Homer-Dixon, pers. comm., 1995).

Water Supply History

In Victoria's earliest days, water was supplied from a spring near present-day Wharf street in downtown Victoria. The spring remained freely accessible until city buildings encroached and the size of the population demanded that a larger water supply be found. In 1858, J.P. Cranford and E. Marvin founded the Spring Ridge Water Supply Company and delivered water at a cost of $1 per 40 "American pails". The spring was located near where Victoria High School stands today (Grant Street and Fernwood Road). An attempt to fence the spring in 1861 drew public outrage, but a steam pump and crude pipe system leading to town were successfully installed a short time later (Hall, 1989).

Victoria's population grew rapidly in the 1860's and 70's. Infrastructure became increasingly important, and roads, parks and utilities were constructed. Water works were constructed in 1874/75 with Elk Lake as the water supply. Water was delivered via a gravity-feed cast iron pipe 30.5 cm (12") in diameter and later replaced with a 40.64 cm (16") rivetted steel pipe (c.

1891) and pumped to the city (c. 1900). The water passed through filter beds at the outlet of the lake and was delivered to a reservoir on Smith Hill where it was distributed by gravity-feed.

The neighbouring naval community of Esquimalt had an independent water supply at this time. Theodore Lubbe founded the Esquimalt Water Works Company and obtained the water rights to Thetis Lake and the Goldstream River area in 1884. In the 1890's an extensive system of ditches and reservoirs was constructed. A pipeline 10 miles long delivered water to Esquimalt from Cabin Pond (Hall, 1989).

By 1908 water demand in Victoria was in excess of 9,090,909 L (9090 m^3) (two million imperial gallons) per day. The Elk Lake supply soon became inadequate to meet the needs of the population and a search was begun for a new source of water.

Many waterbodies were examined for their suitability as a water supply. These included Millstream Creek, (water from Millstream Creek had long been delivered to the City by ship (Hall, 1989)), the Goldstream River, and Sooke Lake. A May 1905 report by Mr. Arthur L. Adams, a consulting engineer from San Francisco, characterizes Sooke Lake thus:

> "Sooke Lake lies about 24 miles, by wagon road, to the west of Victoria. It is a beautiful body of water, of great average depth, the surrounding mountains rising precipitately on every side. The country is virtually uninhabited and remains in its virgin condition. The region never having been surveyed, neither its area nor the extent of its tributary watershed is known. There can be no doubt however, that it is capable of yielding a certain supply very much larger than need for the present purposes be considered necessary, and that the quality be considered satisfactory" (City of Victoria, 1910).

A supplementary report issued in 1907 indicates that there was "little or no outflow from the lake in its natural state during the latter part of each dry season" so it would therefore "be necessary to utilize its storage to produce a constant supply." It was recommended at that time that "its drainage area should be so controlled as to prevent the location of habitation thereon, or summer campers." In order to accomplish this goal, it was recommended

$100,000 be set aside "to cover the acquisition of necessary lands and rights about the lake." Mr. Adams' findings were summarized in a report to City Council who agreed that Sooke Lake should be considered as Victoria's water supply. A subsequent survey conducted by Mr. Wynn Meredith of the engineering firm Sanderson & Porter, showed "conclusively the superiority of Sooke Lake as a source of supply." Its "purity was assured and its flow ample to meet all existing requirements and to permit further development for the prospective additional needs of the city."

Once the suitability of Sooke Lake had been ascertained, the city authorities hired Mr. Meredith to draw up the plans for the supply of 72,727,273 L (16,000,000 imperial gallons) of water daily from Sooke Lake to the City of Victoria. A by-law authorizing the City Council to undertake the Sooke Lake project was successfully put forward for public approval in January 1911. A $1.7 million construction contract was let to Westholme Lumber Company of Vancouver on December 19, 1911. This contract was cancelled on April 12, 1913 and the project taken over by the City (City of Victoria Archives). Due to delay in completing the project, the City began to purchase water from the Esquimalt Water Works Company in May 1913 through a temporary pipeline over the Selkirk Water (Hall, 1989).

The waterworks consisted of a solid concrete dam at the outlet of Sooke Lake which raised the water level 3.7 m (12 feet) and provided a storage capacity of 15,240,994 m^3 (3,355,000,000 imperial gallons). A circular intake tower in the lake contained seven gated openings permitting water to be drawn from various depths. At that time, the engineering firm provided for the future expansion of the reservoir by the construction of a second dam which would raise the water level by an additional 10m (33 feet) (14m/ 45 feet above the original lake level). They proposed that the tributary watershed could be "doubled by diverting the flow of the Leach [sic] River ... through a comparatively short canal and delivering all of the annual runoff from its watershed of 80.3 km^2 (31 square miles) into Sooke Lake except during extreme flood periods" (Sanderson & Porter, c. 1914).

In 1914, construction began on a 107 cm (42") reinforced concrete flowline to deliver water from Sooke Lake 44 km (27.5 mi) to the newly created Humpback Reservoir (Figure 10). From Humpback Reservoir the water flowed through a riveted steel conduit 91.4 cm (36") in diameter to the city. The construction of such a massive project required the installation of rail and telephone lines. The yard for pouring and curing the concrete pipe was 28 km (17.5 mi) south of Sooke Lake at Cooper's Cove. Materials were delivered to this site by water and finished pipe sections were hoisted via a tramway onto the 61 cm (2 foot) gauge construction railway which ran to Sooke Lake. It is noted in the engineers report that grading for the construction of the flowline "was done principally by hand, as all equipment and supplies had to be packed in due to the absence of roads" (Sanderson & Porter, c. 1914). All trees on the pipeline right of way, which was 30.5 m (100 feet) wide, were felled as were any trees outside this swath which could damage the pipeline if they fell. The railway track was removed ahead of the advancing flowline and the concrete sections laid in its place. The conduit was completed and the first water from Sooke Lake delivered to the City of Victoria in May 1915 (Figure 11).

The final cost of construction and initial development of the Sooke Reservoir system was $2,809,764.27 including $578,701.09 for land purchase ($32.13 per acre)– five time the cost estimated by Mr. Adams.

In 1925, the municipalities of Oak Bay and Saanich opted to purchase water from the Esquimalt Waterworks company. At this time, the mayor of Victoria, Carl Pendray, directed city staff to expropriate the company. The Esquimalt Waterworks Company was purchased for $1.5 million, which included lands in the Thetis Lake area. In 1930 a Bill was passed in the provincial legislature, prohibiting trespass on all watershed lands. The combined assets of the early G.V.W.D. and the Esquimalt Water Works Company make up the holdings of the G.V.W.D. as it exists today.

Fire History

The fire history of a watershed is related to climate, aspect, elevation, topography, fuel types and ignition probability, including fire supression activities (Parminter, 1992). Fire plays a direct role in vegetation succession, nutrient cycling, and soil structure and stability of an ecosystem (Murray, 1994). The nature of the surrounding vegetation and soils will determine, in part, the effects of the fire on the neighbouring waterbodies. Mature forests, such as that surrounding Sooke Lake prior to European colonization of Vancouver Island, are characterized by 1) a closed canopy that intercepts much of the rain and snow, 2) a deep forest floor which absorbs moisture and stabilizes slopes and 3) a regime of internal recycling which releases only small amounts of nutrients into nearby waters. Severe fires remove much of the canopy, convert the accumulated fuel on the forest floor to soluble ash, reduce the infiltration capacity of mineral soils by developing water repellancy, increase runoff and erosion and may liberate nutrients into surrounding waterbodies (Wright, 1981).

Sooke Watershed's fire history is important in understanding the water quality history of Sooke Reservoir, because the reservoir is very oligotrophic and thus has the potential for extreme sensitivity to changes in nutrient loading. Goldman *et al.* (1990) found that atmospheric deposition of nutrients from fires elsewhere in the state of California were sufficient to increase primary productivity in Lake Tahoe, an ultra-oligotrophic warm monomictic lake, in spite of reduced light intensity (PAR) from atmospheric smoke and ash on the lake surface. Given the unproductive nature of Sooke Reservoir, one would expect a response similar to that of Lake Tahoe should increased nutrient loading occur.

Two opposing hypotheses are presented in the literature with regard to effect of forest fire on water quality 1) the rapid conversion of living and dead biomass to soluble ash may release large quantities of nutrients to runoff and thus to lakes, causing algal blooms (Tiedemann *et al.*, 1978), 2) the nutrients released following fire are adsorbed in the soil or taken up by vegetative regrowth and stream organisms before they reach lakes, thus having little effect on lake water quality (Tarapchak and Wright, 1986). Furthermore, light reaching the streams will increase due to the loss of cover and may stimulate algal and aquatic plant growth where it had previously been light limited. Several studies have found elevated nutrient levels in streams following fire (McColl and Grigal, 1975; Tiedemann *et al.*, 1978; Wright, 1981), however this does not appear to translate into significantly elevated lake nutrient levels nor algal blooms (McColl and Grigal, 1975; Wright, 1976; Schindler *et al.*, 1980). Preliminary evidence from a paleolimnological study of Rainbow Lake in Wood Buffalo National Park, Alberta supports this hypothesis, suggesting that fire does not cause sufficient change in lake water chemistry to alter the structure of the diatom community in the lake (Moser, 1994; Moser, pers. comm., 1995). In contrast, an increase in algal production and changes in cladoceran community structure were evident in the sedimentary record of Elk Lake, Minnesota following fire (Bass and Boucherele, 1984) and a shift in pH following fire in the Algoma Region of Ontario resulted in a change in diatom community structure which lasted almost forty years (Dickman and Fortescue, 1984).

The magnitude, timing and intensity of fire, watershed soil type, weather and particularly, phytoplankton community structure in the lake may all influence the magnitude of effect that fire has on lakes. For example, a more intense fire will burn the deeper nutrient rich basal layers of the forest floor while a less intense fire, such as a prescribed burn will liberate fewer nutrients by burning only the surface layers which are nutrient poor (Richter *et al.*, 1982). These factors may account for the high degree of variability among studies and among lakes.

Despite disagreement in the literature over nutrient liberation by fire and its effects, most researchers agree that fire does increase soil erosion potential and the loss of vegetation reduces interception and transpiration of water and temporarily increases runoff. An increased sediment influx to the lake may therefore be evident following fire (Wright, 1981). Increased erosion may also be expected to increase aluminum and vanadium flux to the sediments (Cwynar, 1978). Soot particles contained in lake sediments can be used to date the occurrence of fire and assess watershed fire history (Hilgers *et al.*, 1993; Renberg and Wik, 1994) for comparison with other limnological variables (Moser, 1994).

The early fire history of the Sooke Watershed must be reconstructed from field reconnaissance, since records of fires in the area were not kept until the 1920's. General fire histories for the B.C. coast, lower mainland coast and CWH zone indicate that prominent fire years for southern Vancouver Island were : 1489, 1558, 1660, 1684, 1690, 1820 and 1890 (Murray, 1994). Many fires have gone unreported to the Forest Service and thus records are incomplete and underestimate the number of fires that have occurred. In 1994, the Greater Victoria Water District commissioned a study of the fire history and its effects in the Sooke and Goldstream watersheds (Murray, 1994). Fire dates determined from that study are reported here.

The fire regime of the CWH zone consists of crown and surface fires returning every 150-250 years, which typically result in total stand replacement (Parminter, 1990). Fires of lower severity are more common and may also occur within more severe burns. The mean fire return interval calculated for the Sooke watershed is 127 years. The Sooke watershed is divided into 23 regions for fire history purposes. Ten of these areas were found to have stands of trees whose age class indicates that the stand originated between 1885 and 1890 due to fire (Murray, 1994). This would indicate that a major fire or series of smaller fires occurred in the Sooke watershed c. 1890, a prominent fire year, and should be evident in the sediments of Sooke Lake. Numerous other fires have occurred within the watershed. The years in which fire occurred in more than one region are highlighted in Table 7 in bold print.

Neither the long- nor short- term effects of fire on the water quality of Sooke Reservoir can be predicted from existing data, since no studies on this topic have examined coastal British Columbian watersheds. Based on the fire history presented above, one may predict that some evidence of the 1890 fire should be present in Sooke Reservoir sediments, perhaps as soot particles, though it is unclear whether the phytoplankton community can be expected to reveal a change of a long enough duration to be seen in the sediments.

Methods

Coring Procedures

Cores were removed from Sooke Reservoir on three occasions in 1993 and once during 1994: January 28, 1993, June 11, 1993, August 19, 1993 and May 17, 1994. All 1993 cores were taken with a modified Kajak-Brinkhurst-type gravity corer (inside core tube diameter 4.3 cm); 1994 cores were taken using a Glew corer (modified KB) with a 6.35 cm inside core tube diameter (Glew, 1989). All cores were taken from the deepest points of either the north basin (68 m) or south basin (20 m) of Sooke Reservoir and were transported upright and held at room temperature until they were extruded. The coring sites are regular reservoir sample sites for the G.V.W.D. and are marked with permanently anchored buoys. Thus, even though the cores were taken at different times, their location did not differ by more than a few metres. Cores taken in 1993 were sectioned into 0.5, 1 or 2 cm increments using a threaded rod fitted with a bung. The bung was inserted into the lower end of the core tube and used to slowly push the core out the top of the tube where sections were sliced off into containers using a plastic putty knife. The 1994 cores were sectioned into 0.5 cm slices using a Glew extruder according to the methods prescribed for its use (Glew, 1988). A summary of coring dates and sites, core numbers, interval thickness and analyses performed is located in Table 8.

^{210}Pb dating

Subsamples of wet sediment from core #1 (taken January 28, 1993) were submitted to Atomic Energy of Canada for ^{210}Pb analysis according to the microwave acid-digestion technique outlined by Cornett *et al.*, (1984). ^{210}Pb is a natural radioisotope derived from the decay of ^{226}Ra. In lake sediments, it is separated into two components: that derived from the *in-situ* decay of ^{226}Ra, termed "supported ^{210}Pb", and atmospheric inputs derived from secondary decay from ^{226}Rn, the "unsupported ^{210}Pb". The ^{226}Ra is assumed to be in equilibrium with the supported ^{210}Pb fraction (Anderson, 1995). ^{210}Pb has a half-life of 22.26 years; therefore it is unreliable when used to date sediments more than 150 years old.

Upon receipt by the laboratory, samples were dried in an oven at 70°C and subsamples were taken for Pb analysis. Eleven 1-cm core sections were analysed. The 2.0–3.0, 4.0–5.0, 9.0–10.0, 12.0–13.0 and 25.0–26.0 cm sections were analysed in duplicate and the results reported separately. ^{210}Pb concentrations were decay corrected from the counting date to the date of volatilization using a half-life of 138.38 days for ^{210}Po.

The ^{210}Pb concentrations were used to calculate dates for each core section according to both the Constant Initial Concentration (C.I.C.) model of sediment and ^{210}Pb deposition (Robbins, 1978) and checked against the Constant Rate of Supply Model (C.R.S.) (Krishnaswamy *et al.*, 1971). This C.I.C. model assumes that i) the flux of ^{210}Pb to the sediments has been constant with time ii) post deposition migration of Pb does not occur iii) ^{210}Pb supported by ^{226}Ra is independent of depth in sediments and iv) the sedimentation rate has been constant with time (MacDonald *et al.*, 1994). If corrections are made for sediment compaction, age and depth are directly related; therefore, in undisturbed cores, ^{210}Pb concentration values are expected to decline monotonically with depth. If increases in ^{210}Pb concentration with depth are evident, the use of the Constant Rate of Supply (C.R.S.) model is indicated. This model makes only the first three assumptions and considers sedimentation rate as a variable.

Sediment Accumulation Rate (SAR) values for the C.I.C. model were calculated using the arithmetic average rates defined by the linear regression of the cumulative dry sediment mass vs. the Ln of ^{210}Pb activity (Atomic Energy of Canada Limited, 1993). Core depths were converted to years using the regression equation: year = (-7.51 x depth (cm)) + 1989.4 as determined from the C.I.C. model. All reported dates are derived using the C.I.C. model unless otherwise noted.

X-ray Analysis/Densitometry

Two north basin cores and two south basin cores taken May 17, 1994, were X-rayed one week later at Royal Jubilee Hospital using a Shimadzu X-ray machine set at 63 kV and 5.0 mAs for 16 msec. Following X-ray analysis all cores were sectioned at 6-mm intervals using a Glew extruder (June 24, 1994), dried, weighed and archived. (The sectioning interval was intended to be 5 mm, however an error was made when the spacer block for the extruding device was measured). Photographic contact prints were made of each X-ray using standard darkroom techniques. The prints were then computer analysed using Optimas™ video imaging software linked to a Panasonic model WV CP-210 video camera. Each print was marked at 5 mm intervals (0= top of core) down the length of the core. The luminance of each section was measured using the video system calibrated to an artificial computer standard. Lower luminance values indicated darker (ie. denser) layers of the core. These values were recorded and correlated with ^{210} Pb dates, precipitation data and phosphorus data.

Loss-on-Ignition

The percentage of moisture in each section was determined by drying in an oven at 105°C. Aliquots of 1 g were then ignited at 550°C in a muffle furnace for 1 hour and re-weighed. The resulting weight loss was assumed to represent organic carbon (Edmondson, 1969).

Diatom Analyses

Wet samples were weighed using a Mettler model PM 460 digital balance and dried at 80°C to a constant weight (approximately 48 hours) in an incubator. Dry samples were re-weighed and aliquots of 200 µg removed and placed in labelled test tubes to which 10 mL of concentrated chromic acid was added. Samples were heated in a water bath at 80 - 100 °C for 2-4 hours until oxidation appeared complete (no bubbles appeared when tubes were gently shaken). In cases of incomplete oxidation of organic matter, the diatoms were separated from the acid solution by centrifugation and the acid solution pipetted off and replaced with fresh solution. Samples were transferred to 16 mL polypropylene Nalgene™ centrifuge tubes and centrifuged in a Sorvall Superspeed RC2-B centrifuge at 3500 rpm for 15 min and 7000 rpm for 5 minutes. Samples were repeatedly rinsed with 10 mL deionized water and re-centrifuged until pH tested equal to that of the deionized water (≈ 5.8). Samples were then transferred to 31 mL screw cap glass vials and diluted to approximately 20.5 mL. Samples were shaken and a 200µL aliquot removed and suspended in 25 mL of deionized water in a 150 mL beaker. Modified Battarbee settling trays were fitted with 4 coverslips of #1 thickness, 22 mm in diameter and one coverslip 10 mm in diameter and placed inside the drying oven (Battarbee, 1973). The sample was stirred and quickly poured into the settling tray while inside the oven to prevent disturbance. Samples were left to settle and evaporate for 48 hours at 40°C. The four large coverslips were removed from the trays and mounted with Hyrax on 7.5 x 2.5 cm (3" x 1") slides. The 10 mm coverslip was placed into a compartment of a well plate and labelled for later examination using scanning electron microscopy.

Diatom Identification

Diatoms were identified using both light and scanning electron microscopy. Preliminary identifications were made using a Zeiss Photomicroscope II according to the taxonomic works of: Hustedt, 1930; Hustedt, 1962; Sieminska, 1964; Foged, 1964; Patrick and Reimer, 1966; Cleve-Euler, 1968; Camburn, K.E. *et al.*., 1984-86; Barber and Haworth, 1981; Foged, 1981 and Lucey and Austin, 1994. Confirmation of these identifications was made using a JEOL model JSM-35 scanning electron microscope and appropriate primary literature (references). As far as possible, all species were sketched, photographed and catalogued for future reference. Tentative identifications of the nine most abundant species were confirmed, using scanning electron micrographs, by Dr. Eugene Stoermer (University of Michigan), Dr. Rex Lowe (Bowling Green State University) and Deborah Hunter (University of California at Davis). Species were identified as Centric or Pennate and planktonic or benthic, and further categorized as Araphidineae (A), Biraphidineae (B), Monoraphidineae (M) and Raphidiodineae (R). The total number of individuals in each group was totalled for each core section and used to compute benthic to planktonic and Araphidineae to centric ratios.

Diatom Counts

Diatoms were counted using a Zeiss Photomicroscope II at 750X magnification. Pairs of random vernier scale co-ordinates were calculated using the formulae X= (random number) x 20 + 5 and Y= (random number) x 20 + 105 to give X co-ordinates between 5 and 25 and Y co-ordinates between 105 and 125 (McQuoid, unpublished). Random numbers were computer generated. This method of calculation assumes that the coverslip is square and always positioned in exactly the same area of the slide. Since round coverslips were used and the coverslip placement was not always the same, some pairs of co-ordinates were unusable since they did not describe an area on the coverslip. In such instances the co-ordinates were omitted and the next pair was chosen. For each sample, diatoms were counted from these random fields until 600 frustules had been counted. In samples with low diatom density, counting was stopped once 45 fields had been examined. Thirty-seven samples were counted from core 7 and seven replicate samples were counted from core 8.

The relative abundance of each species was determined by dividing the number of valves of the species encountered by the total number of valves counted for all species in that core section. Absolute numbers of valves per gram were calculated as follows:

$$\text{\# valves/g} = \left(\text{\# of valves counted}\right) \times \frac{\text{area of coverslip mm}^2}{\text{no. fields x area of field mm}^2} \times \frac{\text{area of tray mm}^2}{\text{area of coverslip mm}^2} \times \frac{\text{volume of vial mL}}{\text{0.5 mL}} \times \frac{1}{\text{weight of aliquot cleaned g}}$$

Estimation of Diversity

Species richness increases with the complexity of food webs and with the extent of niche overlap (Wetzel, 1983). The dominance of a few species or an abundance of rare species can complicate estimates of species diversity. The Shannon-Weaver diversity index accounts for both relative abundance as well as the total number of species in a population and is therefore commonly used to estimate phytoplankton diversity (Wetzel, 1983). This index was chosen to estimate the diatom diversity in Sooke Lake for the reason given above, as well as to facilitate comparison with other similar studies. The Shannon-Weaver diversity estimate (H') is calculated as follows:

$$H' = -\sum p_i \log_2 p_i \text{ in bits/individual}$$

where p_i is estimated from n_i / N as the proportion of the total population of individuals (N) belonging to the i^{th} species (n_i) (Shannon and Weaver, 1949).

Inference of Historical Phosphorus Values

Weighted averaging calibration was used to infer historical phosphorus concentrations in Sooke Reservoir. This technique has two components: 1) modelling of diatom abundances to varying total-P concentrations and 2) use of modelled responses to infer historical total-P concentrations from diatoms preserved in the lake sediments (Birks *et al.*, 1990). The first component requires a "calibration set" of modern diatom abundances and corresponding lakewater nutrient concentrations. A regression is then performed to ascertain the phosphorus concentration at which maximum abundances of a given species are present. Since no calibration data were available for Sooke Reservoir, published optima from other British Columbia Lakes were used (Cumming *et al.*, 1995; Reavie *et al.*, 1995). Optima for 28 species were located from the first source and 3 additional species were included in the second source. The species and their optima are presented in Table 9. An optimal value for *Aulacoseira italica,* the dominant sedimentary diatom in Sooke Reservoir, was not available. Fortunately, the published optima were accompanied by plates identifying the organisms (Cumming *et al.*, 1995). The Sooke Reservoir species identified as *Aulacoseira italica* did not resemble Cumming *et al*'s plate of *A. italica*. It more closely matched an as yet unidentified species known as *Aulacoseira* cf. sp. 12 PIRLA. Since an optimum was available for the latter species, this value was used in the calibration.

In order to infer historical total-P concentrations, the relative abundance of each species in each core section (as a percentage) was multiplied by the published total-P optimum for that species. The products of all the species were then summed for each core section and divided by the total number of diatoms in each section. This procedure is summarized in the following equation (Birks *et al.*, 1990):

$$\hat{x}_i = \sum_{k=1}^{m} y_{ik}\,\hat{u}_k \Big/ \sum_{k=1}^{m} y_{ik}$$

where $\hat{x}_i$ = the inferred historical total-P value (μg/L) for the specified core section i

y_{ik} = the relative abundance of taxon k in sample i,

(i= 1,...n lakes and k= 1,...m diatom taxa)

$\hat{u}_k$ = the total P optimum of taxon k

Since the necessary deshrinking equations were not provided by Cumming *et al.*, or by Reavie *et al.*, this procedure was not performed. Without deshrinking, low total-P concentrations will have been overestimated and high total-P concentrations will have been underestimated; however, the directions of historical trends will be the same.

Chemical Analyses

Geochemical analyses were performed by Zenon Laboratories, Vancouver, British Columbia. Initial analyses were performed on core #2 (taken January 28, 1993) which was sectioned into 2-cm increments as the core diameter was too small to provide a sufficient quantity of sediment if the interval was reduced. In order to improve resolution, the north basin cores taken on June 11, 1993 were sectioned at 0.5-cm intervals and sections from four cores were combined into single samples for metals analyses. A single south basin core from the same date was sectioned at 1-cm intervals with the intent of combining these samples with samples from a second core for metals analysis, however, the second core was lost during sectioning. The 1-cm sections were analysed successfully.

Levels of Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, P, Pb, Se, Sr, V, and Zn were determined using inductively coupled plasma atomic emission spectroscopy. Samples were dried and ground and digested with nitric-perchloric acid to solubize the solid matter and oxidize and volatilize the organics before spectroscopy (McQuaker, 1987). The same sections were also analysed for Total and Inorganic Carbon and Sulfur using a Leco induction furnace. Organic carbon was calculated by subtracting Total Inorganic Carbon from Total Carbon (Swain and Walton, 1992). Kjeldahl Nitrogen analyses followed McQuaker (1987). The sample was first digested in boiling sulfuric acid to convert N compounds to ammonium bisulfate. Alkali was then added to liberate the ammonia and the solution was distilled into a boric acid solution for titration with sulfuric acid. Minimum detectable concentrations (MDC) for all metals was 1 µg/g dry weight except for Al, As, Co, Pb and Sn for which the MDC was 10 µg/g and Ni and P for which it was 5 µg/g.

Results

Core Description

Core #7, the principal core used for diatom analysis, was taken from Sooke Reservoir on August 29, 1993. Its total length was 62 cm; however, only the top 46.5 cm were sectioned. While sectioning the core the sediments appeared soft and organic, medium brown in colour and were somewhat sticky. There was no discernable odour indicating that the sediments were not anoxic. The top 2 mm of sediment were finely textured and light tan in colour. At 4 cm, a less dense layer extended downward for approximately 1 cm. Between 10 and 11 cm, a dark layer of medium texture appeared, followed immediately by a finer orange layer approximately 0.5 cm thick and a lighter brown layer approximately 1 cm thick. A barely discernable darker layer, appearing almost as a shadow, appeared between 16 and 17 cm. Below 17 cm the core was homogenous in colour and texture. Photographs of the core were taken prior to sectioning; however, reflection of light off of the core tube obscured the details of the core and rendered the photographs unusable.

Core #8, taken at the same time as core #7, was 55 cm in length. The top 42.5 cm were sectioned for analysis. It too had a fine, light layer approximately 2 mm thick at the surface. Between 10 and 11.5 cm a black, coarse layer was evident interspersed with orange particles which appeared to be iron oxide. A concentrated region of orange particles appeared at 12.5 cm. A lighter clay-like layer was evident between 14 and 16 cm. Below 16 cm the core was finely textured and homogeneous in colour.

When dried, the sections from both cores were pale grey and firm, not crumbly. Black particles, possibly oxides of manganese, appeared throughout the core. Many sections left an orange residue on the plastic of the core container- possibly iron oxide. The 5.0- 5.5 cm section of core #7 contained black particles which resembled soot. The 8.5-9.0 cm section was very dark upon drying. Section 9.5 to 10.0 was very orange and contained a noticeably larger number of black particles. The 10.5- 11.0 cm and 11.0-11.5 cm sections were also orange and appeared very coarse with aggregates of fine material. At 28.0-28.5 cm the core contained whitish aggregates which were thought to be pollen upon initial examination, though this was not confirmed at a later date.

^{210}Pb dating

Analysis for ^{210}Pb showed a concentration decreasing from 0.30 to 0.07 Bq/g in about 4 cm (Figure 12). This decrease corresponded to a period of approximately 44 years as calculated by the C.I.C. model. The dates calculated using both the C.I.C. model and C.R.S. model, for those core sections analysed, are compared in Table 10. It should be noted that C.I.C. dates are reported from the midpoint of each core section while C.R.S. dates are reported from the top of the core section.

The C.I.C. calculated date for the 20.0- 21.0 cm core section was 1837 (S.E. 0.369), indicating that these sediments were deposited before European settlement of Vancouver Island. The date estimate calculated with the C.R.S. model suggests that this section is approximately a decade younger. It should be noted however, that ^{210}Pb dating is not reliable for sediments older than 150 years and dates pre-1850 should be interpreted with caution. The sediment accumulation rate (SAR) was calculated using the C.I.C. calculated dates and found to have a range of 1.12 to 1.68 mm/yr (Figure 13). The mean SAR is 1.35 mm/yr. Maximum sediment accumulation occurred in the eighteenth century (precise dates not reliable), while the lowest rate of accumulation occurred during the years 1898-1918.

C.R.S. dates corresponded closely with those calculated using the C.I.C. model (Table 10) with a few exceptions. The C.R.S. model suggests that the 2.0-3.0 cm section is approximately 4 years younger than that predicted by the C.I.C. model; however, this difference is about the same as the uncertainty inherent in the models themselves. In contrast, the 6.0-7.0 cm and 9.0-10.0 cm sections are shown to be 8.0 years older using the C.R.S. model than that predicted by the C.I.C. model (1930 vs. 1938; 1910 vs. 1918).

X-ray Analysis

A visual examination of the of two fresh North Basin cores showed little vertical differentiation. X-ray analysis however, revealed differentiated

The identity of five of the nine most abundant species was independently confirmed by three outside experts using scanning electron micrographs (Figures 17-19). Table 12 contains a comparison of the experts' diatom identifications and comments. The dominant species were, in decreasing order of abundance, *Aulacoseira italica* (Ehrenb.) Simonsen, *Cyclotella michiganiana* Skvort., *Cyclotella ocellata* Pant., *Cyclotella stelligera (Cleve & Grun. in Cleve)*, *Cyclotella bodanica* Grun. in Schneider, *Cyclotella meneghiniana* Kütz., *Asterionella formosa* Hass., *Tabellaria fenestrata* (Lyngb.) Kütz. and *Stephanodiscus astraea* (Ehr.) Grunow. *Aulacoseira italica* was the dominant diatom throughout the core (Figures 20 and 21). Below depths of 15 cm (1877) very little change occurred in the relative abundance of the nine species listed above. Post-1877, a shift in abundance occurred: *Tabellaria fenestrata*, *Asterionella formosa*, and *Cyclotella ocellata* reached their peak abundances between 1905 and 1920 and *C. stelligera*, *C. bodanica*, *C. michiganiana* and *C. meneghiniana* all declined in abundance in the same period.

In order to place the diatom data in proper chronological order, data from the lower (older) sections of the core are presented first. *T. fenestrata* represented less than 2% of the population prior to 1875 (Figure 22). It then increased to a peak relative abundance of 7% in c. 1916 and then declined abruptly between 1916 and 1927. Post-1927 its abundance never exceeded 2%. *A. formosa* populations followed a similar pattern (Figure 23). *A formosa* was present in very low numbers prior to 1875. The population then increased rapidly, reaching 22% in 1916, and then fell abruptly to 3% thereafter. The increase in *C. ocellata* and *S. astraea* populations occurred prior to that of *T. fenestrata* and *A. formosa*. *C. ocellata* populations increased from less than 10% in the lower sections of the core to approximately 30% in 1905 (Figure 24). The population then slowly declined to 5% in 1931. In the upper 8 cm of the core, *C. ocellata* abundance was comparatively constant, ranging between 6 and 11 %. *S. astraea* increased from less than 1% prior to 1879 to 2.5% in 1897 and then returned to its former abundance in the 1930's (Figure 25).

Of the four species which showed an increased relative abundance in the upper 15 cm, *C. stelligera* showed the strongest upward trend (Figure 26). Its relative abundance was very low (< 7%) before 1929 with the exception of an unexplained peak of 25% in 1835. From 1929 onward, its relative abundance increased steadily, peaking at 25% in 1974. The increases in *C. bodanica* and *C. michiganiana* abundance began earlier, in 1912 (Figures 27 and 28). By 1927 the populations appeared to plateau at relative abundances of 4 and 14%, respectively. The increase in C. *meneghiniana* coincided with that of C. *stelligera*, C. *bodanica* and C. *michiganiana*, however a sharp decrease in abundance began in 1950 and by 1965 the species had disappeared entirely (Figure 29).

Diversity

Diatom diversity, as measured by the Shannon-Weaver diversity estimate, ranged between 2.64 and 3.67 bits/individual (Figure 30). The lowest diversity values lie in the 1905- 1920 cm interval, and reflect the increase in relative abundance of *Tabellaria fenestrata* and *Asterionella formosa*.

A/C ratio

The A: C ratio in Sooke Reservoir is very low (mean 0.03) and stable prior to 1882 (Figure 31). Between 1875 and 1916 it increases by a factor of 10 from 0.050 to 0.475. It then declines rapidly to a value of 0.025 in 1950. Between 1950 and the present it stabilized around 0.045 (mean).

Chemostratigraphy

With the exceptions of nickel and cobalt, metal concentrations were the least variable prior to 1896 (13 cm) (Figures 32 and 34). These low, constant concentrations are taken to represent natural background levels. Both vanadium and zinc concentrations steadily increased beginning in 1886 (13.75 cm) and stabilized in 1914 (10 cm) at concentrations 21% and 34% above background, respectively. Vanadium concentrations have declined in recent decades to natural background levels, while zinc remained elevated.

Arsenic, barium, copper, iron, manganese and molybdenum showed trends similar to those of vanadium and zinc, though the trends were asynchronous. Prior to 1899 (12 cm) arsenic concentrations were lower than the limits of detection (10 µg/g) by the ICP method (Figure 32). Between 1901 and 1969, (11.75 - 2.75 cm) values ranged between 10 and 21 µg/g, with peaks in 1918 (9.5 cm) and 1969 (2.75 cm). The second arsenic peak coincided with similar increases in barium, manganese and molybdenum. The barium profile shows two smaller peaks in 1931 and 1938 (Figure 35) rather than the single large peak seen c. 1918 in the other metals. The trend in copper concentration, was almost identical to that of vanadium, increasing 15% over the background concentration of 55 µg/g before returning to near background levels between 1965 and the present (Figure 33).

Pre-1901, (11.75 cm) iron concentrations were low 49.3- 64.8 mg/g (Figure 32). By 1905 (11.25 cm) the concentration increased markedly, approaching 100.0 mg/g. Though highly variable, these elevated levels persisted until 1957 (4.25 cm) and then decline to background concentration.

Trends in cadmium and lead were substantially different from the other eight metals (Figure 33). Prior to 1886 (13.75 cm) neither cadmium nor lead was detectable. Between 1890 and 1916 (13.25– 9.75 cm), lead peaked at 23 µg/g and then again declined to levels below detection. A second, double peak was evident in 1950 and 1961 (5.25–3.75 cm) and levels remained above detection between 1976 and the surface. Cadmium showed a similar trend, peaking in the 1909-1912 interval (10.75-10.25 cm) and in 1954 (4.75 cm). Both cadmium peaks were values of 2 µg/g, a very low value, only twice that of the detection limit.

The lead concentration profile shown in Figure 34 differs from that seen in the preliminary lead analysis. Preliminary analysis, using 2 cm core sections, showed that lead concentrations were below the limit of detection prior to 1944 (Figure 34). Lead levels peaked in 1974 and then declined to the present.

Discussion

Chronology

Obtaining a reliable estimate of the age of lake sediments is fundamental to successfully using paleolimnology as a tool for interpreting past lake conditions or changes. Chronologies can be affected by many factors including catchment disturbance, changing sediment loads to lakes, bio- or mechanical turbation and eutrophication (Anderson, 1995). It is therefore essential to ensure that the model used and assumptions made in the calculation of the chronology are suited to the water body under study. In the case of Sooke Reservoir, one of the key questions to be answered is whether or not sedimentation rates have changed as a result of catchment disturbance.

The model used to calculate dates for each core section was the Constant Initial Concentration (C.I.C.) model of sediment and ^{210}Pb deposition (Robbins, 1978). This method assumes that 1) the rate of ^{210}Pb supply and 2) the rate of sediment accumulation have remained constant during the dating period, 3) post-depositional migration of Pb does not occur and 4) ^{210}Pb supported by ^{226}Ra is independent of depth in the sediments (MacDonald *et al.*, 1994). A second model, the Constant Rate of Supply model (C.R.S.) differs from the C.I.C. model by treating sedimentation rate as a variable. This model is appropriate if there is reason to believe that the sedimentation rate has changed substantially over time (Anderson, 1995). Such a change would be evident from an inflection in the ^{210}Pb profile with depth. Only a very slight inflection near the surface was evident in the ^{210}Pb profile from Sooke Reservoir. Since surface sediments are uncompacted relative to deeper sediments, such inflections are common and do not significantly alter the accuracy the C.I.C. model (Oldfield and Appleby, 1984). Another possible cause for this inflection is the migration of ^{210}Pb through the sediment-water interface through the interstitial waters (Oldfield and Appleby, 1984). Since no inflection appeared with depth (Figure 12), the C.I.C. model was considered appropriate, though C.R.S. dates were calculated for comparison.

Further confirmation of the chronology is evident in the geochemical data collected. Initial geochemical analysis for Pb showed a sharp increase in concentration in 1945 followed by a decline in 1974 (Figure 34). This coincides with the addition of lead to gasoline in the post- World War II era and its subsequent removal beginning in 1971. Furthermore, barium, arsenic, molybdenum and manganese peaks coincident with clearing around the reservoir in 1912/13 and 1969/70 lend further support to the chronology and thus to the sediment accumulation rate. Since the x-rays show horizontal bands of differing densities throughout two north basin cores, bio- or mechanical turbation can be ruled out. The lack of bands in the south basin cores suggests mixing of the sediments and therefore the north basin chronology is not applicable to the south basin.

The presence of the dark, dense bands throughout the entire length of both North Basin cores (Figure 14), suggests that the bands were caused by a natural phenomenon. If the bands were due to increased erosion caused by anthropogenic disturbance, they would not likely appear until the early 1850's when Vancouver Island was settled by Europeans. The bands appear to correspond to 20-30 year intervals, and may be the result of sediment mobilization during exceptionally heavy precipitation events. In X-rayed cores from Lake Washington, 250 km south of Vancouver Island, Edmondson (1991) found pairs of cryptic layers which he examined by electron microscopy. He found that the light layers were composed mostly of diatoms, while the darker, denser layers were dominated by mineral particles. He attributed variation in the thickness and composition of the dark layers to differences in the annual input of clay and silt during fall and winter storms. Storms may also account for the variability in the sediment accumulation rate in Sooke Reservoir.

The highest sediment accumulation rates (SAR) in Sooke Reservoir occur prior to the turn of the 20th century (Figure 13). This chronology, like the x-rays, suggests a natural cause for the variations in sediment input to the reservoir. Sedimentation rate historically ranges between 1.1 and 1.7 mm per year. The higher values do not seem to be related to incidence of fire; however, this conclusion is based upon a reconstructed fire history which is likely to be somewhat inaccurate simply due to the difficulty of such a task.

Between 1873 and 1891 the SAR is 1.7 mm/yr and between 1918 and 1938 it is 1.6. Though these values are within the range of natural variability, they are slightly higher than the rates in decades immediately preceding or following them. These values correspond to slight increases in total organic carbon during these periods (Figure 15) however it is not possible to determine the cause of this covariance from these data. The lowest sediment accumulation rates occur between the 1940's and the present, during which road construction, logging and dam construction all occurred. Human activity within the Sooke watershed does not then appear to have increased the sediment input to the reservoir beyond its natural maximum. These data also indicate that the production of phytoplankton biomass within the reservoir has not substantially increased as a result of human activities.

Diatom Stratigraphy

Diversity

The Shannon-Weaver index is a distribution-free measure of diversity. Therefore, the introduction of a new species to the community or the transfer of abundance from a more abundant to a less abundant species, will increase the diversity measure (van Dam, 1973). If however, two species "change places" ie. a very abundant species becomes scarce and a rare species becomes very abundant, the diversity measure will not change. Diversity is maximal when all species have equal relative abundance; that is, when the maximum number of niches are occupied. The narrow range of diversity values (2.64-3.67 bits/individual) implies that the mix of diatom species in Sooke Reservoir may have changed over time, but the species are always distributed in roughly the same proportions.

The decrease in diversity between 9-11 cm reflects the rapid increase in relative abundance of both *Tabellaria fenestrata* and *Asterionella formosa*. (Figure 30). Though *C. stelligera*, *C. bodanica*, *C. Kützingiana* and *C. meneghiniana* all decreased in abundance in this same interval, *T. fenestrata* and *A. formosa* increased more rapidly than the *Cyclotella* species declined and a decrease in diversity is therefore evident.

A:C Ratio

Stockner and Benson (1967) proposed that the relative abundance of planktonic and littoral diatoms in the sediments of a lake is a useful indicator of the relative significance of, and change in, littoral and planktonic events in lake history. In 1971, Stockner suggested that the ratio of Araphidineae (mostly littoral) to Centric (mostly planktonic) species could be used to classify lakes on the basis of trophic status. He based this conclusion on an examination of sediments from Lake Washington (USA), Windermere (UK), Linsley Pond (USA) and the Experimental Lakes Area (Canada). The araphidinate species included in this index were *Asterionella formosa**, *Synedra acus*, *S. delicatissima*, *Fragilaria crotonensis*, *F. construens** and *Tabellaria fenestrata**. The centric species included *Aulacoseira italica**, *Cyclotella stelligera**, *C. ocellata**, *C. comta*, *C. comensis*, *C. Kützingiana*, *C. striata*, *C. glomerata* and *Stephanodiscus astraea**. Those species marked with an asterisk are also present in Sooke Reservoir.

When assessing the trophic status of lakes, single indicator species have been more commonly used than the A:C ratio. The difficulty with the single species method is that taxonomic precision is key to an assessment and one can never be sure whether a species' presence or absence is due to the physical and chemical status of the lake or to more nebulous factors such as parasitism, predation or competition (Battarbee, 1986; Stockner, 1971, 1972). Furthermore, lakes with similar chemical and physical composition may sustain very different species (Hetherington *et al.*, 1993; Brown and Austin, 1973), rendering "common" indicator species useless. In contrast, application of the A:C ratio is not precluded in lakes that do not contain "common" indicator species, and it does not require precise taxonomic identification.

According to Stockner's classification, lakes with an A:C ratio of 0-1.0 are considered oligotrophic, 1.0-2.0 mesotrophic and those with a value >2.0, eutrophic. Thus, an increase in the A:C ratio may be interpreted as an increase in primary production. Sooke Reservoir is consistently well within the oligotrophic category; however, the increase from 0.05 to 0.48 between the years 1882 and 1916 (Figure 31), suggests that the reservoir may have undergone some form of nutrient enrichment in this period. The decline in the A:C ratio to a value of 0.25 in 1950, a period of 34 years, suggests that either a) the nutrient addition decreased gradually b) a fixed nutrient pool was exhausted over time or c) some other mechanism controlled algal production in the reservoir. A relatively consistent ratio of 0.45 (mean) between 1952 and the present suggests that the reservoir has returned to equilibrium. This is consistent with Ostrofsky's trophic upsurge model which predicts the establishment of a new biological equilibrium once the physical and chemical constituents have stabilized following impoundment (Ostrofsky, 1978) (Figure 36).

The A:C index has been evaluated by Brugam (1979), Brugam and Patterson (1983) and Battarbee (1986) amongst others. From his examination of eighty Minnesota Lakes, Brugam concluded that high A:C ratios were characteristic only of lakes with moderate total phosphorus levels and very low alkalinities. Brugam also found an increase in small *Stephanodiscus* species in disturbed Minnesota lakes which led him to conclude that the A:C index was not valid for those lakes. This suggests a fundamental difference between the Pacific Northwest and the upper midwest (Brugam and Vallarino, 1989). This difference may be accounted for by the lower phosphorus concentrations in coastal lakes (Hardy *et al.*, 1986). If the small *Stephanodiscus* species require high phosphorus concentrations they would not appear in coastal lakes (Brugam and Vallarino, 1989). Since the phosphorus concentrations in Sooke Reservoir are extremely low, the A:C ratio should hold true due to the absence of small ratio-skewing *Stephanodiscus* species.

In their 1989 study of four Western Washington lakes, Brugam and Vallarino noted that increased abundance of *Asterionella formosa* was a consistently strong indicator of watershed disturbance. This confirms Stockner's earlier findings and is consistent with trends seen in Sooke Reservoir. Of the 125 species observed in Sooke Reservoir sediments, *A. formosa* underwent the most significant change in abundance. This shift strongly influences the A:C ratio, supporting Stockner's hypothesis that this index can be used as an indicator of watershed disturbance. It is interesting to note, that while the change in the A:C ratio is very dramatic prior to the construction of the first dam, no such change is evident during construction of the second dam, nor during the commencement of logging activities on Sooke watershed lands.

A 1984 paleolimnological study of nearby Shawnigan Lake found a similar trend to that seen in Sooke Reservoir (Nordin and McKean, 1984). Shawnigan Lake is a popular recreation site and has been subject to increasing watershed disturbance since the early part of this century. Much of the watershed has been logged and the shoreline and watershed have been extensively developed for both year-round and summer residential housing. A sediment core from Shawnigan Lake showed a marked increase in abundance of *A. formosa* and *T. fenestrata* at a depth of 6 cm concomitant with a decline in *Melosira (Aulacoseira) distans*, *Cyclotella bodanica*, and *C. stelligera*. This change persisted to 1984. The increase in Araphidinate species coupled with a decline in centric species suggests that the A:C ratio is a also a good indicator of disturbance in this watershed.

Edmondson (1991) suggested that while the A:C index cannot be regarded as a general index of eutrophication, a definite mechanism must exist to explain the shift seen in some lakes. One hypothesis is that an increase in the A:C ratio is not a result of increased Araphidinate production, but rather a reduction in the number of centric species. Chemical inhibition of centric diatom growth by cyanobacteria, particularly *Oscillatoria*, is suggested, as is differential grazing by zooplankton (Edmondson, 1991).

Whether or not the A:C ratio can be used as an index of "eutrophication" or phosphorus loading *per se*, it does indicate an altered trophic dynamic in Sooke Reservoir. The increase in the A:C ratio (Figure 30) coincides with a decline in both the total number of diatom frustules and the number of centric frustules reaching the sediment (Figure 16). The increase in the A:C ratio then, is not a result of increasing Araphidineae abundance, but rather a decline in centric diatom abundance as Edmondson suggested (1991). A mechanism must therefore exist which preferentially selects against centric diatoms. Differential grazing by zooplankton is one possible mechanism.

The increase in the A:C ratio in Sooke Reservoir coincides with the establishment of a fishing camp on Sooke Lake in the early 1880's. Anecdotal records indicate that large 1.25 kg cutthroat trout were caught by fishermen on Sooke Lake at that time. However, Sooke Reservoir has been closed to fishing since its establishment as a drinking water supply. The lake survey conducted by the provincial government (Balkwill, 1991) confirms that cutthroat trout were the dominant fish in the reservoir in 1959. The fact that all the fish caught were immature, would suggest that a comparable number of mature fish must have spawned in tributary creeks (Appendix A). Anecdotal information indicates that Sooke Reservoir continues to support a population of very large trout which may approximate the historical condition of the lake. The importance of these fish to the phytoplankton within the Sooke Reservoir ecosystem may have been historically underestimated.

Mazumder *et al.*, (1989, 1990a, 1990b, 1992) have demonstrated that freshwater phytoplankton community biomass can be experimentally manipulated by altering the density of fish populations in large *in-situ* enclosures. The grazing pressure exerted by fish keeps zooplankton populations in check and, in turn, removes grazing pressure from phytoplankton. If the fish are removed, the grazing pressure on zooplankton is released and the zooplankton population increases until the supply of food (phytoplankton) is exhausted. Grazing effects are known to be strong in oligotrophic systems and even small-bodied zooplankton can reduce nutrient-limited phytoplankton populations under the right conditions (McQueen *et al.*, 1986). If large numbers of small trout, or small numbers of large trout, were removed from Sooke Lake by patrons of the fishing camp, then grazing pressure on the zooplankton may have been lessened and have allowed them to graze more heavily on the phytoplankton. In the absence of historical fisheries data, an estimate of annual fish production in pounds/acre x year can be made using the morphoedaphic index (Ryder, 1965; Leach *et al.*, 1987).

$$\text{Annual fish production } (Y) = 2\sqrt{X}$$

where X= morphoedaphic index = total dissolved solids (ppm)/ mean depth (feet).

The mean depth of Sooke Lake was 18.0 m (60.0 feet) (Table 1) and the concentration of total dissolved solids can be estimated by dividing the present mean specific conductance in half (44.5 µS/cm ÷ 2= 22.25 ppm) (Table 2). This gives an estimate of the annual fish production in Sooke Reservoir of 1.22 lbs/acre x year or 1.37 kg/ha x year. The total annual fish production of the original lake was very low, in the order of 509 kg/yr (surface area= 372 ha). The removal of a few hundred fish per year could therefore result in the loss of a significant proportion of the annual fish production and radically alter the trophic interactions within the lake.

Mazumder *et al.* (1989, 1990a, 1990b, 1992) conducted in-situ grazing experiments using large enclosures in oligo-mesotrophic lakes in Ontario. When planktivorous fish were removed from the system, abundance and community filtering rates of meso-zooplankton increased while abundance of micro-zooplankton decreased. The biomass of larger microplankton (20-200 µm) also increased and the fraction of total phosphorous sedimenting was higher. Meso-zooplankton were also shown to be less selective than micro-zooplankton when grazing on the nano-phytoplankton (2.0- 20µm) and were better able to reduce nano-phytoplankton abundance by exerting similar grazing pressure on all nano-plankton particles. Abundant micro-zooplankton were not able to reduce nano-phytoplankton abundance.

Examination of light micrographs of the phytoplankton in Mazumder *et al.*'s (1992) enclosures, shows that the community composition of the control enclosures is very similar to the present phytoplankton community in Sooke Reservoir. Sedimentary diatom evidence shows that the present phytoplankton community, with planktivorous fish, is very similar to the historical community. Mazumder *et al.*'s theory of tropho-dynamics suggests that under natural conditions, the zooplankton community of Sooke Reservoir was dominated by micro-zooplankton which were unable to graze down the nano-phytoplankton. Given the oligotrophic nature of this waterbody, the phytoplankton were likely kept in check by nutrient limitation (Stockner and Shortreed, 1988). Smaller phytoplankton, particularly the pico-phytoplankton, are known to have higher nutrient uptake rates than larger nano- and micro-phytoplankton and thus can outcompete them for nutrients under nutrient-limited conditions (Stockner, 1991; Suttle *et al.*, 1991). Once the fish predation was reduced following the opening of the fishing camp, the meso-zooplankton population, which is the most vulnerable to fish predation, increased and the nano-phytoplankton, still nutrient-limited, were grazed down. Since both *Asterionella formosa* and *Tabellaria fenestrata* are larger micro-phytoplankton, the zooplankton may have been unable to feed upon them. As the proportion of small, centric diatoms decreased, the relative abundance of the large Araphidinate diatoms increased.

The above theory is supported by a 1990 study of an eutrophic Danish lake, which demonstrated that planktivorous fish removal caused a shift in the zooplankton community from rotifer–dominated to cladoceran–dominated (Sondergaard *et al.*, 1990). A similar Norwegian study showed an increase in *Daphnia sp.* abundance from <1% of total biomass before planktivorous fish removal to >90% after biomanipulation (Lyche *et al.*, 1990). In the Danish study, this shift in the zooplankton community was accompanied by a change in the composition in the phytoplankton community. Prior to fish removal, the dominant phytoplankton were cyanobacteria and small diatoms, particularly *Stephanodiscus hantzchii* and *Melosira (Aulacoseira) distans*. Following fish removal, larger *Asterionella* spp. dominated the phytoplankton community. Mean summer phytoplankton biomass decreased by half the first year and to one third the historical values by the second year. Both the increase in *Asterionella* sp. and the decrease in overall number of cells fits the trend seen in Sooke Reservoir.

Following the purchase of the Sooke watershed lands by the G.V.W.D., the fishing camp was closed. As the fish populations rebounded, the meso-zooplankton populations were once again grazed down. The nano-phytoplankton populations were then free to increase to the point of nutrient-limitation and the relative proportion of micro-phytoplankton (araphidinate species *A. formosa* and *T. fenestrata*) once again declined.

This explanation of change in the phytoplankton community structure in Sooke Reservoir is undoubtedly an oversimplification. Zooplankton are known to have at least two counter-acting effects on phytoplankton populations: a) reduction of algal standing crop through grazing and b) stimulation of algal growth through nutrient regeneration (Bergquist and Carpenter, 1986). Detailed studies of zooplankton food preferences have shown the traditional size-efficiency hypotheses to be incorrect. One cannot accurately predict food size, and therefore phytoplankton fraction eaten, simply from body size of zooplankton as is frequently assumed (Bogdan and Gilbert, 1984). Algal response to grazing may also differ among algal taxa and among lakes. Since response is so variable it must be assessed on a lake-by-lake basis. Also, the role of small planktivorous fish and insects in the control of the phytoplankton community of Sooke Reservoir is unknown.

It is difficult to assess historical standing algal crop using paleolimnological techniques for a number of reasons. Firstly, only one component of the phytoplankton community, the diatoms, is usually studied. Scales of colonial chrysophyte algae also preserve well in sediments (Smol, 1980; 1988), however ten chrysophyte scales may represent anywhere between one and ten individuals, thus one cannot estimate, with accuracy, their true abundance, relative to the phytoplankton community as a whole. Pigment residue analysis techniques offer some insight into the presence of other algal taxa but quantification is difficult (Gorham and Sanger, 1975). Attempts to quantify standing crop, using total organic carbon measurements, are also deceptively simple: as zooplankton grazing releases phosphorus, algal growth rate increases, and phytoplankton decrease their C:P ratio (Lyche *et al.*, 1990). The relative contribution of different phytoplankton components to the biomass also differs widely among systems. In coastal oligotrophic lakes, algal picoplankton (0.2 - 2.0 μm) can contribute 50-70% of the total annual carbon production (Stockner and Shortreed, 1989; 1991). At present, a method has not yet been determined to retroactively assess the relative contribution of each phytoplankton fraction to the annual carbon budget of a lake. In any case, there appears to be very little data that could link watershed activities such as dam construction, logging or fire, with a change in the carbon budget of Sooke Reservoir.

Metal Analyses

Metal concentrations in sediments reflect those of the overlying water column and surrounding watershed. The concentrations within the sediments tend to be much higher than those of the water column making them easier to analyze with greater precision and accuracy than water samples (Demayo *et al.*, 1978). In an historical context, lake sediments act as a repository for metals, enabling trends in concentration to be examined at a later date. It is not possible, however, to equate sediment concentration with water column concentration directly.

Many factors can influence post-depositional metal concentrations in sediments including: chemical form of the metal and surrounding sediment, oxidation and reduction processes, crystallinity, surface area, bioturbation, bioavailability for benthic organisms and sediment resuspension (Rieberger, 1992). It is unlikely that disturbance processes have altered the metal profiles of Sooke Reservoir sediments. The reservoir has an oxic hypolimnion and sediment-water interface, which prevents the reduction and subsequent liberation of most metals. The point in the reservoir from which the cores were taken is very deep, 68 m, thus currents are unlikely to mechanically resuspend sediment. No benthic organisms were observed in the sediment cores and the ^{210}Pb profile was even, thus bioturbation appears unlikely. It is therefore reasonable to conclude that the metal trends seen in the Sooke Reservoir are real (Figures 32 and 33).

British Columbia can be divided into six physiographic regions based upon tectonic and geological processes (Rieberger, 1992; Farley, 1979). Sooke Reservoir is within the southern sub-region of the Insular Belt, an area composed of heavily faulted unmetamorphosed volcanic and sedimentary rock. Copper and iron ore are found throughout this region (Farley, 1979). Rieberger (1992) examined the sediments of 83 lakes in this region and calculated mean concentrations for 25 metals, inorganic, organic and total carbon as well as Kjeldahl N and volatiles (Table 13). Methods used to analyse these samples were identical to those used to analyse Sooke Reservoir samples. The range of values determined for Sooke Reservoir were compared to those found in lakes elsewhere on Vancouver Island. The 18 metals common to this study and that of Rieberger (1992) are grouped by magnitude of concentration and plotted in Figures 37 to 39.

Aluminum levels in Sooke Reservoir are consistently higher than those found in lakes elsewhere on Vancouver Island (Figure 37) and iron (Figure 39) is also somewhat elevated. The source of these metals may be the Al and Fe rich Ferro-Humic Podzols found throughout much of the area (Vallentine *et al.*, 1978). The minimum concentration of nickel in Sooke Reservoir is three times higher than the mean concentration of nickel in the other lakes (Figure 38) though the reason for this is unknown. In contrast, arsenic and magnesium concentrations in Sooke are less than half the mean concentrations determined in Rieberger's study and lead is marginally lower (Figures 38 and 39). While depressed Mg levels are characteristic of podzol soils, the low arsenic concentrations cannot be explained. Calcium, phosphorus (Figure 37), cadmium, chromium, cobalt, copper, molybdenum, strontium, vanadium, zinc (Figure 38), manganese and barium (Figure 39) concentrations approximate those found in surrounding lakes.

Copper, cadmium, lead, vanadium and zinc are all considered 'airborne' metals, that is, elevated concentrations are often the result of atmospheric deposition. The close correspondence of these metal concentrations in Sooke Reservoir with those in surrounding Vancouver Island lakes, suggests that a) the analyses are likely accurate and b) the influence of the airshed on metal concentrations in Sooke reservoir is not unlike its influence in neighbouring regions. The onset of upward trends in copper, vanadium and zinc concentrations coincides with European settlement of Vancouver Island and the construction of smelters in the Seattle area. This lends further evidence to the accuracy of the ^{210}Pb chronology.

In freshwater systems, geochemical data are often used as background information to interpret historical biological/limnological changes (Gorham *et al.*, 1974). In the marine system, increasing attention is being directed toward finding geochemical proxies for biological productivity (Dymond *et al.*, 1992). For example, aluminum and aluminosilicate have both been shown to be well correlated with organic carbon; however, spatial heterogeneity varies over two orders of magnitude. Concentration of Aluminosilicates by zooplankton filtering may account for the relationship between organic carbon and aluminum flux; however the quantity of aluminosilicate debris available to be filtered by the zooplankton is strongly dependent upon location and independent of productivity. Zooplankton therefore seem to act as carriers of aluminum (Dymond *et al.*, 1992) rather than concentrators. In contrast, barium has recently been shown to be very strongly correlated with organic carbon, apparently independent of geographical location. Its use as a proxy for marine biological productivity is becoming widespread (Gingele and Damhke, 1994), though it is not yet used in similar freshwater studies.

Within the marine water column, barium is found primarily in the form of barite ($BaSO_4$) and contributes up to 90% of the total barium in the sediments in some areas of the South Atlantic (Gingele and Damhke, 1994). Early studies suggested that the barite /organic carbon link was a result of barium precipitation by marine haptophyte microalgae (Fresnel *et al.*, 1979 in Dymond *et al.*, 1992). Subsequent studies have disproved this hypothesis and suggested instead that barite is formed in the water column during the breakdown of organic matter (Bishop, 1988).

With regard to algal precipitation of barium, some exclusively freshwater algae are known to actively form barite; notably the desmids which form barite granules in terminal vacuoles (Brook, 1980). These granules, previously thought to be composed of calcium sulphate, are thought to act as statoliths since they are found in the motile desmid genera: *Pleurotaenium*, *Penium* and *Closterium* (Bold and Wynne, 1985). Though many desmids are benthic, several species such as *Closterium limnetica* are planktonic and may contribute to the barium flux to the sediment in some lakes. In very shallow lakes/ponds or nearshore environments the desmid-mediated flux of barite to the sediments may be more significant since both the benthic and planktonic species would contribute.

The formation of barite is thought to be catalysed by the remains of siliceous algae in marine systems (Dehairs *et al.*, 1980). The fresh silica surfaces exposed during the breakup of diatom frustules may adsorb barium better than other surfaces (Bishop, 1988). The same process may also occur in lakes. The release of sulphur from the decaying organisms could provide the necessary sulphur source for barite formation. This may be especially true in the sulphur-poor freshwater environment. Since settling of biogenic particles is known to play an important role in transporting copper and zinc to lake sediments (Sigg *et al.*, 1987) it may also be a significant transport mechanism for other heavy metals.

In one of the very few freshwater studies of barium, McGrath *et al.* (1989) found that the major depositional flux of barium occurred during the summer months when primary productivity was highest. They attributed this to uptake of barium by the algal standing crop and subsequent release through grazing by *Loxodes sp.*, a ciliated protozoan known to accumulate and release barite as discrete granules (Finlay *et al.*, 1983). Whether barium flux to the sediment is increased by active algal uptake or passive precipitation upon algal decay, is not clear. Elevated sedimentary concentrations of barium do however appear to be correlated with increased primary production, both in marine and freshwater systems. Further studies are necessary to elucidate the mechanisms and potential differences between the two systems before barium can be used as a proxy measure of production in freshwater systems.

When examined in the context of a tracer of primary production, the downcore barium profile from Sooke Reservoir is very striking (Figures 32 and 35). Three very strong peaks are evident, all of them post-European settlement. Prior to 1880, the barium concentration in the sediments is very consistent, ranging between 390 and 420 µg/g dry weight. A slight increase is evident between 1880 and 1912 to 450 µg/g. Between 1912, when dam construction was first initiated and 1931, the concentration increases more than 30%. The concentration then begins to decline with the exception of an unexplained peak in 1938. By 1954 the concentration has once again returned to 19th century levels. In 1969, the same year that land clearing was begun for the second dam, the highest peak occurs (770 µg/g). Values then decline rapidly back to predisturbance levels. The temporal correlation of elevated barium concentrations in Sooke Reservoir with land clearing activities suggests two possible causes. Barium may have been mobilized from exposed soils and passively reached the reservoir sediments. This possibility cannot be discounted. Alternatively, land disturbance may have resulted in elevated nutrient concentrations within the reservoir water column with a corresponding increase in algal production. The algae may have concentrated the barium, or the siliceous diatom frustules may have precipitated it from the water column as they sank. Given the evidence from marine systems, increased algal production and subsequent passive barium precipitation seems a likely scenario; however, it cannot be proved without an analysis of the relative fractions of barium in the bulk estimate. Also, total organic carbon and diatom accumulation profiles do not show the same trend as barium and thus it appears that barium has increased as a result of catchment disturbance rather than biologically mediated concentration.

Nutrient Analyses

Phosphorus is often a limiting nutrient in freshwater systems. Relationships between phosphorus and algal production (chlorophyll concentration) are well established (Sakamoto, 1966; Vollenweider, 1968; Dillon and Rigler, 1974). For this reason, paleolimnologists have sought means of assessing historical phosphorus concentrations in lakes as a proxy of their trophic status over time. Weighted-averaging calibration is a commonly used technique (Hall and Smol, 1992; ter Braak and Juggins, 1993). When this technique was applied to Sooke Reservoir, the inferred total-P concentration was found to range between 8 and 12.0 µg/L using Cumming *et al.*'s calibration set and between 9.5 and 14.5 µg/L using Reavie *et al.*'s expanded calibration set (Figure 40). The single high peak (Cumming *et al.* estimate: 12 µg/L; Reavie *et al.* estimate: 14.5 µg/L) appeared in 1916 coincident with the peak in *Asterionella formosa* abundance. These values are almost twice the median present day concentration in the reservoir (Table 2). Deshrinking of these estimates would further improve their accuracy, though the direction of the trends in total-p concentration would remain the same.

The accuracy of historical phosphorus concentration assessment is directly dependent upon the accuracy of the calibration set. The ideal calibration set would come from the same lake on which the assessment was to be done. The calibration sets used in this study, were created by correlating the abundance of individual diatom species in surface sediment with chemical variables in the overlying water column (Cumming *et al.*, 1995;

Reavie *et al.*, 1995)). The accuracy of this technique is questionable, because the diatom remains in the sediment may not reflect the composition of the overlying water column at the time the water chemistry samples were taken. A more accurate method would involve analysing both phytoplankton species composition and water chemistry simultaneously from the water column. As stated earlier, coastal lakes are known to be very different from interior lakes both in lower nutrient concentration and more complex food web dynamics. Thus, the calibration set derived from interior lakes may not be applicable to coastal lakes. In this regard, the historical total-P profile inferred for Sooke Reservoir must be regarded as an indicator only: that is, the trends probably have some validity (Figure 40) but the absolute values must be treated with caution.

The inferred phosphorus profile reflects the increased variation in the diatom community following impoundment (Figure 20). This may be a result of varying seasonal water levels and shoreline sediment exposure caused by the operation of the reservoir. The drawdown of reservoirs affects the phosphorus cycle by altering the amount of phosphorus released from sediments and changing their buffering capacity (Twinch, 1987). The rates of these processes depend upon the duration of desiccation (Linnik *et al.*, 1994), the physical-chemical variability of the environment, the geological composition of the catchment basin and the trophic status of the lake (Mhamdi *et al.*, 1994). As the water level in the reservoir is lowered, greater areas of sediment are exposed to the atmosphere. Part of the sediment is then resuspended as the water level rises and phosphorus is resolubized (Fabre, 1988). The quantity of P released into the overlying water varies according to the speed with which the water level rises, degree of disturbance form local weather and with the concentration of P in the overlying water (Fabre, 1988). Low P concentration in the water favours sedimentary P release. Phosphorus release following drawdown also depends upon the composition of the sediments. The degree of sediment heterogeneity within the reservoir must therefore be ascertained before predictions can be made regarding the relative contribution of sediment P release to the overall P budget of the reservoir (Fabre and Patau-Albertini, 1986). If sediments have previously been dehydrated, bioavailable phosphorus is more readily released. Inundation of previously dehydrated sediment may therefore liberate large quantities of phosphorus in a short period of time (Twinch, 1987).

Increased variability in diatom community composition may result from an ever-changing P concentration within Sooke Reservoir. Prior to dam construction, the lake water P concentration was presumably in equilibrium with sedimentary P concentration. Reservoir operations post- 1913 caused shorelines sediments to be repeatedly exposed and re-inundated. Twinch's study suggests that this may have resulted in progressively greater amounts of phosphorus being released into the overlying water column (1987). This effect could have been compounded by the inundation of new areas, and thus a new nutrient supply, following the construction of the second dam. Repeated sediment exposure and inundation as well as inundation of new areas may also have altered the relative supply of phosphorus from allochthonous vs. autochthonous sources.

Due to the key role phosphorus is known to play in regulating algal productivity in freshwater, it has been the focus of most studies of sediment nutrient release. Recent studies have shown that sediment desorption of ammonium (NH_4+) may also increase dramatically (2- 4 X) following re-inundation of dehydrated sediments (Linnik *et al.*, 1994). This has significant implications for algal community composition, since recent work by Suttle and Harrison (1986) has shown that N and P can limit different components of the phytoplankton community simultaneously. Therefore, reservoir drawdown may not only affect absolute concentrations of nutrients available to algae, it may control the ratio and forms of nutrients and thus have considerable influence on community structure.

Summary

Prior to European settlement, the Sooke Lake ecosystem was very stable. The natural inter-annual variability in the diatom community was small and the sedimentary metal concentrations were low and stable. With the settlement of the surrounding areas and increased industrialization in the U.S. Pacific Northwest, increases in airborne metal concentrations began to be evident in the sediments of Sooke Reservoir. Shortly afterward, c. 1885, a change in the phytoplankton community structure took place. The absolute number of diatom cells reaching the sediments declined, and the ratio of Araphidinate diatoms to Centric diatoms increased. This shift coincided with the establishment of a fishing camp on Sooke Lake from which large cutthroat trout were caught. This likely shifted the zooplankton community toward species with increased filtering rates (e.g. large cladocerans) and reduced the standing crop of phytoplankton. The zooplankton were less able to feed on the larger araphid diatoms and their abundance increased, relative to the other smaller species. Following the purchase of Sooke watershed lands by the G.V.W.D. and the closure of the fishing camp, I believe that trout populations increased and reduced the meso-zooplankton population. The algal community slowly returned to its historical composition. The influence of dam construction is most conspicuous in the geochemical profile of the reservoir sediments. It does not appear to have had a long-term impact on the phytoplankton community within the reservoir. Sedimentation rates within the reservoir are consistently low, and were highest in the eighteenth century.

The phytoplankton community composition has been more variable since the construction of the first dam. This may be a result of varying seasonal water levels and/or nutrient loading from exposed shoreline sediments. Though the community appears to be quite resilient, it also provides evidence of a high degree of sensitivity to changes in nutrient concentration and trophic disturbance. In order to accurately predict the effect(s) of disturbance on the phytoplankton, the disturbance threshold must be quantified. This threshold can be defined as the degree of alteration needed to cause a permanent shift in community composition. The susceptibility of the phytoplankton community to irreversible alteration cannot be determined from this historical study but may be ascertained *in-situ* under present conditions.

Conclusion

The Sooke Reservoir ecosystem is, like all ecosystems, extremely complex. The complexities of this particular system have been compounded by external forces including: removal of fish, flooding of surrounding lands, construction of an extensive road and rail network, alteration of natural drainage patterns, drawdown and sediment exposure, hypolimnetic withdrawal, removal of large quantities of vegetation from the watershed, excavation of deltaic sediment deposits within the reservoir and suppression of natural fire regimes. These confounding factors make it extremely difficult, if not impossible, to confirm the effect(s) of any single historical action on the phytoplankton community within the reservoir or to predict the effects on the phytoplankton of future actions. This study demonstrates that the phytoplankton community of Sooke Reservoir is extremely sensitive to change in the short term. It also shows that the system was historically quite resilient and was able to integrate change and return to "natural" conditions within a few decades. What cannot be addressed by this study is whether the proposed future changes fall below the threshold required to cause significant long-term alteration in the phytoplankton community, nor what the effect on the phytoplankton to community might be if two otherwise insignificant events occurred simultaneously. Since ecosystem response to disturbance is often non-linear we cannot say with certainty that raising the level of the reservoir in the future will have the same effect as it did in the past.

In spite of the limitations of paleolimnological studies, they provide key information. Though fine details often cannot be reconstructed, general trends essential to managing lakes and reservoirs are clarified. This study does not definitively determine what did happen in Sooke Reservoir in the last 250 years but does tell us what did not happen: no major, permanent shifts in phytoplankton abundance or composition are evident, sedimentation rate has not increased as a result of watershed disturbance and sediment geochemical composition is not substantially different from historical conditions. The elimination of possibilities provides a guide for future research and alerts us to areas in which we must be cautious in the future.

Recommendations

The volume of existing ecological information on Sooke Reservoir is very scant. This situation must be corrected if informed decisions are to be made regarding reservoir management. Since fish appear to play a key role in controlling phytoplankton composition and abundance, and thus water quality, an updated lake/fish survey is essential. The role of fish in controlling insect/zooplankton/phytoplankton interactions, could be verified by a paleolimnological study of the historical insect and zooplankton populations, undertaken together with a modern survey of existing insect, phyto- and zooplankton populations to assess their seasonal variability.

The ecology of Sooke Reservoir is inextricably linked to its physical characteristics and water dynamics. An accurate water balance model must be created for this reservoir, by taking actual field measurements of precipitation, gauging of all the major streams, measuring all outflow (not just consumption) and determining accurate water residence time(s). Nutrient data must be collected simultaneously in order to assess relative nutrient inputs from streams and internal sources and create a nutrient budget for the reservoir. Basic information such as which fish species live in the reservoir and how much water flows in and out of the reservoir each year, is critical to managing sensitive organisms such as the phytoplankton and their trophic consequences.

Since phytoplankton directly influence the taste, odour and clarity of the water, management strategies must be designed to maintain the plankton in the most predictable, balanced state possible. In order to do this, variation in such physical characteristics as water level and residence time must be minimized. If raising the water level of the reservoir will minimize drawdown in the future, then it is likely to have a positive long-term effect on the phytoplankton community. This study demonstrates however, that the phytoplankton are very sensitive to change, and therefore undesirable changes in phytoplankton abundance and species composition are likely to result in the short term. Since the threshold of irreversible ecological change is not known, and it is not known whether this change would be positive or negative from a human perspective, future disturbance should be avoided where possible. Within the 20th century Sooke Reservoir will have been raised three times. With this in mind, reservoir management and planning should consider the needs of the Southern Vancouver Island population a century or more from now and plan for those needs today, so that future reservoir disturbance can be minimized.

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Tables

Table 1. Morphometric characteristics of Sooke Reservoir at four stages of development.

Feature	*Formula*	*Units*	*symbol*	*original lake (pre-1913)*	*1913-1970*	*1970-present*	*future (post 1998)*
Elevation	measured	m		171	174.2	180.7	187
Length	measured	m	l	6436		6855	
Maximum width	measured	m	w	804.5		1463	
Maximum depth	measured	m	z_{max}	58.0 (approx.)	61.5 (approx.)	68	74.3
Surface area	measured	ha	A	372.2	435.9	607.1	750.6
Volume	calculated from bathymetry	m^3	V	67.7×10^6	84.1×10^6	120.0×10^6	170.0×10^6
Length of Shoreline	measured	m	L			2.40×10^4	
Mean depth (V/A)		m	z	18.19	19.29	19.76	22.65
Volume development	$Dv = 3 (Z/Z_{max})$		Dv	0.94	0.94	0.91	0.91
Mean depth: maximum depth ratio	Z/Z_{max}			0.31	0.31	0.30	0.30
Area of littoral zone < 7 m depth		ha				165	
Watershed area	measured	ha		7070	7070	7070	7070
Water residence time	volume: output ratio	year				2.0	
Flushing Rate	output:volume ratio	year	ρ			0.5	
Phosphorus Sedimentation coefficient (mean)	$1/(1+\sqrt{\rho})$		R			0.58	

Table 2. Water Quality Summary for 1 to 3 m depth integrated samples at Station 4 (North Basin Deep Station) on Sooke Reservoir. Values in shaded boxes should be used with caution.

Parameter	GVWD Abbreviation	Units	# of Samples	Median	Range	Sampling Dates
Alkalinity	ALKTI	mg/L as CaCO3	98	16.9	14.2-26.3	06/89-07/93
Colour, True	COLTR	TCU	67	7.94	0.88-17.5	04/90 - 07/93
Conductivity	COND25	µS/cm @ 25°C	84	44.5	22.5-50.2	04/90 - 07/93
Dissolved Oxygen	DO	mg/L	76	9.7	7.9-12.1	04/90 - 07/93
Iron	FE	mg/L	27	0.034	0.005-0.082	06/89 - 08/92
Manganese	MN	mg/L	27	0.003	0.00046-0.009	06/89 - 08/92
Ammonia	NH4	mg/L as N	59	0.005	0.0005 - 0.12	06/89 - 09/91
Nitrite	NO2	mg/L as N	7	0.5	0.0005-0.5	04/90 - 05/90
Nitrate	NO3	mg/L as N	59	0.006	0.0015 - 0.837	03/90 - 08/92
Nitrate, Dissolved	NO3D	mg/L as N	13	8.94	1- 44.5	10/92-06/93
Nitrate plus Nitrite	NO2 NO3	mg/L as N	16	0.005	0.005-0.057	06/89-03/90
Ortho Phosphate, dissolved	OPO4D	µg/L as P	15	0.25	0.25-0.556	01/92 - 06/93
Ortho Phosphate, Total	OPO4T	µg/L as P	75	0.5	0.18 - 9.00	06/89 - 08/92
Total Kjeldahl Nitrogen	TKN	mg/L as N	88	0.25	0.061- 0.95	06/89 - 06/93
Total Phosphate	TPO4	µg/L as P	88	3.65	0.44- 28.0	06/89 - 06/93
Total Phosphate, Dissolved	TPO4D	µg/L as P	15	2.26	0.5 - 5.27	06/92 - 06/93
pH	PH	pH units	101	7.4	6.4 - 7.79	06/89 - 07/93
Total Organic Carbon	TOC	units not recorded	38	2.35	0.5 - 6.6	06/89 - 05/93
Turbidity	TURB	NTU	87	0.3	0.08 - 0.93	03/90 - 06/93
Water Temp.	WTEMP	°C	53	14	2.75 - 23	04/90 - 06/93

Table 3. Summary of wetland and forest area inundated by three successive dams on the Sooke River: 1913, 1970, 1998 (Hugh Hamilton Ltd., 1994).

Description	Surface area of Reservoir (ha)	Volume (m^3)	Wetland area inundated (ha)	Forest land inundated (ha)	Total area inundated (ha)	Cumulative area inundated (ha)
Original Lake	372.2	67.7 x 10^6	n/a	n/a	n/a	n/a
Reservoir after construction of first dam in 1912	435.9	84.1 x 10^6	24.2	39.3	63.7	63.7
Reservoir after construction of second dam in 1970 (1970-present)	607.1	120.0 x 10^6	36.9	134.3	171.2	234.9
Future 187m (1998)	750.6	170.0 x 10^6	10.1	133.4	143.5	378.4

Table 4. Summary of biogeoclimatic characteristics of the Sooke Watershed (Meidinger and Pojar, 1991)

Characteristic	Value
Climate	Csb Cfb
degree days over 6 °C	2500 to 3500
frost free days	150 to 250
mean annual temperature	9 to 11 °C
January mean temperature	1 to 4 °C
July mean temperature	16 to 19 °C
5 to 7 months above 10 °C	0 months below 0 °C
snowfall to 25 to 107 cm	3 to 10% of total precipitation
driest month precipitation	1.5 to 4.8 cm
wettest month precipitation	12.7 to 26.4 cm
clouds: common in winter	rare in summer
elevation S.E. Vancouver Island	0 to 450 meters
latitude	48° to 50°20"N (in the rain shadow of Vancouver Island mountains).

Table 5. Streams within the Sooke Reservoir catchment area (Axys, 1994) (R. Boyd, pers. comm., 1995).

Stream number/ name	Rank Order	Volume contrib. to Sooke Res. (dam3) (% inflow)	Tributary	Area (ha)	Main-stem length (m)	Order	Remarks
1/ Whiskey	3			400	1,300	2	Gentle low to mid reaches
			1a	8	700	1	Wetland source
2/ Judge	2			1,000	5,000	2	Mainly gentle gradients; wetlands in mid & upper reaches
			2a	5	300	1	Joins judge below 175 m elevation
3/ Begbie	4			300	1,600	2	Extensive wetland and small lake on lower reach; low gradient
			3a	4	75	1	Wetland; low gradient
			3b	5	125	1	Wetland; low gradient
			3c	8	400	1	Low gradient
			3d	20	600	1	Crosses Sooke Main; moderate gradients on higher reaches
			3e	6	225	1	Low gradients
4/ "11S"	10			8	500	1	Crosses Sooke main near 11S; channel incised into fluvioglacial sediments
5	9			10	700	1	Crosses Sooke Main; steep upper reaches
			5a	4	300	1	Crosses Sooke Main; steep upper reaches
6	13			4	400	1	Irregular channel gradient
7	13			4	350	1	Gentle gradients in lower and mid reaches; steep upper reaches; no defined channel above 192 m.
8	13			4	350	1	Steep upper reaches; short length of defined channel above 192 m.

9	14			3	300	1	Steep upper reaches; short length of defined channel above 192 m.
10/Rithet	1			2,250	7,000	3	Largest sub-basin; gentle to moderate gradients on mainstem; only stream with year-round flow
11	13			4	350	1	Very steep upper reaches
12/ "15S"	11			7	500	1	Very steep upper reaches
13/Horton	5			330	3,200	2	Steep upper reaches, heavy bedload; associated alluvial fan
14/17S	7			190	1,700	2	Steep upper reaches, heavy bedload; associated alluvial fan; mid-reach has been channelized
15	14			3	300	1	Moderate gradients mid-reach; gentle upper reach gradients
16/Daisy Patch	8			150	950	1	Lower reaches have moderate gradients; upper reaches are gentle; crosses Leechtown main near spur 1A1
17/ Ever-Running	12			5	450	1	Moderate to steep upper reaches
18/Hummingbird	6			250	2,200	2	Most of catchment in gentle higher elevation plateau
			18a	25	1,000	1	Moderate channel gradients

Table 6. Chronology of events within the Sooke watershed.

Year	Event
1843	James Douglas arrives with 15 Hudson's Bay employees to establish a fort on Southern Vancouver Island
1858	Population of Fort Victoria still less than 500 people
1860	A prominent fire year on Southern Vancouver Island
1861	Government trail built along the Sooke River
1862	Incorporation of the City of Victoria
1864	Gold Rush begins on the Leech River
1864 (est.)	Healy farm established on the site presently occupied by Deception Reservoir
1865	Road built from Victoria to Leechtown
1866	Leech River gold rush ends
1871	B.C. becomes a Canadian province
1875 (est.)	Trail built from Cobble Hill to Victoria along the shores of Shawnigan and Sooke Lakes.
1884	Cobble Hill-Victoria trail upgraded to a wagon road
1884 (est.)	William Healey opens a fishing camp on the Sooke Lake
1888	E & N railroad built, bypassing Sooke Lake
1890	A prominent fire year on Southern Vancouver Island
1905, May	Sooke Lake first examined as a water supply source
1911	Construction of the Canadian Northern Pacific Railway started
1911	Sooke watershed lands purchased by the City of Victoria
1911-1914	Construction of the first dam on the outflow of Sooke Lake
1914	Construction of the concrete flowline from Sooke Reservoir to Humpback Reservoir
1915, May	First water delivered from Sooke Reservoir to Victoria
1919	Talc quarry opened on Old Wolf Creek by W.G. Dickenson
1920's	Kapoor Logging Company begins logging in the Goldstream watershed.
1923, Fall	C.N.P. Railway reaches Lake Cowichan
1925	Expropriation of the Esquimalt Waterworks Company by the City of Victoria.
1929-1939	"Relief" camp established on the present site of the (1970) dam.
1929-1939	Relief camp workers constructed a road from the south end of Sooke Reservoir to the present intersection of 23S and Sooke Lake Main
1951	Logging begun in the Sooke watershed at the north end of the reservoir
1957	"3S" area first logged

1957	Construction of Sooke Lake Main begun across the north end of the reservoir
1957/58	area north of the shop up to "11S" logged
1959	Rithet Creek bridge constructed
1960/61	Logging begins on the west side of the Rithet Valley
1961	Sooke Lake Main completed along the west side of the reservoir
1968	Clearing around the reservoir begins.
1968	Council Creek diversion constructed
1968	Highway 117 (Leechtown Main) relocated up the hillside
1969	Soils from Rithet delta excavated (approx. 2 ha) in preparation for construction of the 1970 dam
1970	a channel 1 m deep dug between the north and south basins of Sooke Reservoir
1970 (Feb. 4)	Water tops the spillway of the new (1970) dam
1977	CN rail line used to haul world's tallest flagpole out of Rithet Creek over the Kosilah trestle. Line rarely used again.

Table 7. Prominent fire years in the Coastal Western Hemlock biogeoclimatic zone. The years in which fire occured in more than one "fire region" of the Sooke watershed are highlighted in bold print.

Century	Fire Years
12th- 16th	1185, 1390, 1458, 1490, 1520, 1524, 1570, 1578, 1590
17th	1635, 1650, 1655, 1663, 1665,**1670, 1685,** 1690, 1695
18th	1710, 1715, 1728, 1733, **1735,** 1743, **1745,** 1750, 1755, 1760, 1765, **1790**
19th	1800, 1803, 1810, 1818, 1840, **1860,** 1884, 1885-1890, 1886-1903, 1888, **1890**, 1890-98
20th	1900, 1903, 1905, 1908, 1920, 1927, 1930, 1942, 1945, 1951, 1983

Table 8. Summary of coring dates and sites, core numbers, interval thickness and analyses performed on sediment cores from Sooke Reservoir.

Coring Date	Coring Site	Core Number	Thickness of Core Sections	Analyses Performed
Jan. 28, 1993	North Basin	#1	1 cm	^{210}Pb dating
Jan. 28, 1993	North Basin	#2	2 cm	ICP metals scan
June 11, 1993	North Basin	#3	0.5 cm	cores #3-#6 combined for ICP metals scan
June 11, 1993	North Basin	#4	0.5 cm	
June 11, 1993	North Basin	#5	0.5 cm	
June 11, 1993	North Basin	#6	0.5 cm	
June 11, 1993	South Basin	#S1	1.0 cm	ICP metals scan
Aug. 19, 1993	North Basin	#7	0.5 cm	diatoms
Aug. 19, 1993	North Basin	#8	0.5 cm	diatoms
May 17, 1994	North Basin	#9	0.6 cm	X-ray
May 17, 1994	North Basin	#10	0.6 cm	X-ray
May 17, 1994	South Basin	#S2	0.6 cm	X-ray
May 17, 1994	South Basin	#S3	0.6 cm	X-ray

Table 9. Species and total phosphorus optima used in weighted averaging calibration to infer historical total phosphorus concentrations in Sooke Reservoir.

Species	**Total P optimum (µg/L) (Cumming *et al.*, 1995)**	**Total P optimum (µg/L) (Reavie *et al.*, 1995)**
Achnanthes clevei	11.6	12.1
Achnanthes exigua	n/a	12.8
Achnanthes lanceolata	12.2	15.0
Achnanthes linearis	n/a	10.6
Achnanthes microcephala	8.8	10.1
Achnanthes minutissima	9.0	13.5
Asterionella formosa	11.8	14.6
Aulacoseira cf. sp. 12 PIRLA	6.8	6.8
Cocconeis placentula var. placentula	12.8	18.3
Cyclotella bodanica	11.7	11.6
Cyclotella meneghiniana	8.9	10.7
Cyclotella michiganiana	10.0	26.3
Cyclotella ocellata	14.5	19.5
Cyclotella stelligera	9.7	13.5
Cymbella minuta	10.1	9.8
Fragilaria construens	16.5	20.5
Fragilaria crotonensis	13.8	17.6
Gomphonema subtile	21.5	10.9
Gyrosigma acuminatum	20.6	22.0
Navicula cryptocephala	10.7	9.5
Navicula pupula	11.9	14.0
Navicula radiosa	10.2	11.8
Nitzschia palea	n/a	17.9
Rhopalodia gibba	10.9	11.9
Stauroneis anceps	21.0	20.7
Stauroneis phoenicenteron	9.6	9.1
Stephanodiscus alpinus	11.3	11.9
Synedra radians	8.9	9.2
Synedra ulna	10.7	n/a
Tabellaria fenestrata	9.5	10.8
Tabellaria flocculosa	15.0	17.9
Urosolenia eriensis	n/a	11.8

Table 10. Results of ^{210}Pb analysis performed on a sediment core from the North Basin of Sooke Reservoir

Section Depth (cm)	Depth to which CIC and CRS dates refer	^{210}Pb (Bq/g)	Decay corr. to volatilization date (Bq/g)	Dry Wt. of section slice(g)	CIC Calculated dates	CRS Calculated dates	Sedimen-tation Rate (CRS Model) g/m2 x yr
	0.0					1993	
0.0-1.0	-0.05	0.248	0.295		1989		255.99
	-1.0					1988	
1.0-2.0	-1.5						204.17
	-2.0					1981	
2.0-3.0	-2.5	0.291	0.330	0.885	1972		152.13
2.0-3.0	**-2.5**	**0.288**	**0.343**	**0.885**	**1972**		
	-3.0					1972	
3.0-4.0	-3.5						136.22
	-4.0					1960	
4.0-5.0	-4.5	0.200	0.227	4.630	1955		117.76
	-4.5	**0.209**	**0.237**	**4.630**	**1955**		
	-5.0					1947	
5.0-6.0	-5.5						116.58
	-6.0					1934	
6.0-7.0	-6.5	0.075	0.085	8.255	1938		156.03
	-7.0					1925	
7.0-8.0	-7.5						166.49
	-8.0					1919	
8.0-8.5	-8.5						175.61
	-9.0					1913	
9.0-10.0	-9.5	0.041	0.046	12.625	1918		191.05
	-9.5	0.033	0.040	12.625	1918		
	-10.0					1907	
10.0-11.0	-10.5						225.82
	-11.0					1897	
11.012.0	-11.5						225.89
	-12.0					1892	
12.0-13.0	-12.5	0.020	0.023	18.500	1891		252.02

	-12.5	0.020	0.024	18.500	1891		
	-13.0					1888	
13.0-14.0	-13.5						213.09
	-14.0					1882	
14.0-15.0	-14.5						175.40
	-15.0					1878	
15.0-16.0	-15.5	0.022	0.025	22.445	1873		151.53
	-16.0					1871	
16.0-17.0	-16.5						195.97
	-17.0					1865	
17.0-18.0	-17.5						231.62
	-18.0					1859	
18.0-19.0	-18.5						251.86
	-19.0					1855	
19.0-20.0	-19.5						258.79
	-20.0					1851	
20.0-21.0	-20.5	0.013	0.015	30.335	1837		267.22
25.0-26.0	-25.5	0.011	0.013	38.880	1798		
	-25.5	0.011	0.013	38.880	1798		
29.0-30.0	-29.5	0.010	0.012	45.910	1766		
32.0-33.0	-32.5	0.010	0.011	49.805	1748		

Table 11. List of species encountered in two sediment cores from the North Basin of Sooke Reservoir.

Diatom Species Identifications	**Identifications to Genus/ tentative species identifications**
Achanthes minutissima Kutz.	*Achnanthes delicatula-like*
Achnanthes affinis	*Achnanthes peragalli ?*
Achnanthes clevei Grun. in Cleve & Grun.	*Achnanthes/Cocconeis sp.?*
Achnanthes exigua Grun. in Cleve & Grun.	*Anomoneis sp.*
Achnanthes lanceolata (Breb. ex. Kutz.) Grun. in Cleve & Grun.	*Cocconeis sp.*
Achnanthes lemmermanni	*Cocconeis sp. 1*
Achnanthes linearis (W.Sm.) Grun.	*Coscinodiscus sp.*
Achnanthes microcephala (Kutz.) Cleve auct. non Kutz.	*Cyclotella bodanica (large)*
Achnanthes sp.	*Cymbella sp.*
Amphipleura pelludicida (Kutz.) Kutz.	*Cymbella sp.1*
Amphora ovalis	*Denticula sp.*
Asterionella formosa var. formosa Hass.	*Diatoma sp.*
Asterionella formosa var. gracillima	*Diploneis oculata-like*
Caloneis alpestris	*Diploneis sp.*
Cocconeis pediculus	*Diploneis sp. 1*
Cocconeis placentula	*Epithemia sp.*
Cyclotella bodanica Grun. in Schneider	*Eunotia sp.*
Cyclotella michiganiana	*Fragilaria sp.*
Cyclotella meneghiniana Kutz.	*Fragilaria sp. 1*
Cyclotella ocellata Pant.	*Fragilaria sp. 2*
Cyclotella stelligera (Cleve & Grun. in Cleve) Van Heurck	*Fragilaria sp. 3*
Cymbella cistula	*Gomphonema sp.*
Cymbella lunata	*Mastogloea sp.*
Cymbella minuta Hilse ex. Rabenh.	*Melosira distans (robust form)*
Diploneis elliptica	*Melosira granulata?*
Diploneis finnica	*Melosira sp. 1*
Diploneis puella	*Melosira sp. 2*
Epithemia turgida (Ehrenb.) Kutz.	*Melosira sp. 3*
Eunotia arcus Ehrenb.	*Melosira sp. 4*
Eunotia elegans	*Melosira sp. 5*
Eunotia flexuosa	*Navicula pelliculosa?*
Eunotia serra	*Navicula sp.*
Fragilaria construens	*Navicula sp. 1*
Fragilaria crotonensis Kitt.	*Navicula sp. 2*
Fragilaria mesolepta	*Navicula sp. 3*
Frustulia rhomboides var. saxonica	*Navicula sp. 4*
Frustulia rhomboidea	*Navicula sp. 5*
Gomphonema acuminatum var. coronatum	*Navicula sp. B*
Gomphonema gracile Ehrenb.	*Navicula sp. D*
Gomphonema subclavatum	*Neidium sp.?*
Gomphonema subtile Ehrenb.	*Nitzschia palea?*
Gyrosigma acuminatum (Kutz.) Rabenh.	*Nitzschia sp.*

Aulacoseira distans (Ehrenb.) Simonsen	*Pinnularia sp.*
Aulacoseira italica (Ehrenb.) Simonsen	*Stauroneis sp.*
Navicula aurora Sovereign	*Stauroneis sp. 1*
Navicula bacillum Ehrenb.	*Surirella sp.*
Navicula cryptocephala Kutz.	*Surirella turgida?*
Navicula elegans	*Synedra sp.*
Navicula elginensis	*Tabellaria fenestrata (long)*
Navicula inflexa	*Tetracyclus ?*
Navicula pupula Kutz.	
Navicula radiosa Kutz.	
Navicula robusta	
Navicula salinarum Grun. in Cleve & Grun.	
Navicula vanheurkii	
Neidium iridis	
Nitzschia linearis	
Pinnularia abaujensis	
Pinnularia viridis	
Rhopalodia gibba (Ehrenb.) O. Mull.	
Rhopalodia gibba var. ventricosa	
Stauroneis anceps Ehrenb.	
Stauroneis anceps v. linearis	
Stauroneis obtusa	
Stauroneis phoenicenteron (Nitzsch) Ehrenb.	
Stephanodiscus astraea (Ehr.) Grunow	
Surirella linearis	
Surirella robusta	
Synedra filiformis	
Synedra radians Kutz.	
Synedra rumpens	
Synedra ulna (Nitzsch) Ehrenb.	
Tabellaria fenestrata var. fenestrata	
Tabellaria flocculosa	
Urosolenia eriensis	

Table 12. Comparison of diatom species identifications made by outside experts from scanning electron micrographs (Figures 17-19).

Tentative Identification	Dr. Eugene Stoermer University of Michigan	Dr. Rex Lowe Bowling Green State University	Deborah Hunter, U. of California at Davis	Conclusion
Cyclotella bodanica Eulenstein	*C. bodanica* Eulenstein- future changes forthcoming	*C. bodanica* Eulenstein , or an oligotrophic form of *C. comta*	*Cyclotella bodanica* Eulenstein	*Cyclotella bodanica* Eulenstein
Cyclotella ocellata Pantocsek	*C. ocellata* Pantoscek OK also called *C. tripartita* Håkansson	*C. ocellata* Pantoscek	*C. ocellata* Pantoscek	*Cyclotella ocellata* Pantoscek
Cyclotella kuetzingiana Thwaites	possibly *C. michiganiana*	*C. michiganiana*- tangentially undulate with strutted process in the valley	*C. kuetzingiana* however very small. similar to *C. caspia* found in brackish water	*Cyclotella michiganiana* Skvort.
Cyclotella kuetzingiana (underside)	not identifiable, not likely same as previous specimen	*C. michiganiana*	see above	*Cyclotella michiganiana* Skvort.
Cyclotella stelligera Cleve et Grunow	perhaps *C. stelligera* see also *C. stelligeroides*- perhaps "ring of fire" distribution	*C. stelligera* Cleve et Grunow OK	*C. glomerata* Bachmann	*Cyclotella stelligera* Cleve et Grunow
Stephanodiscus astraea (Ehr.) Grunow	perhaps undescribed. unknown	uncertain. *S. astraea* perhaps correct	very small for *S. astrae.a* More likely *S. alpinus* Hustedt (an oligo. form)	*Stephanodiscus astraea (Ehr.) Grunow*
Stephanodiscus astraea (Ehr.) Grunow	likely from *S. transilvanicus* complex	uncertain. *S. astraea* perhaps correct		*Stephanodiscus transilvanicus* ?
Melosira (Aulacoseira) distans (Ehrenb.) Simonsen	*Aulacoseira italica* variety	*Aulacoseira distans*	*Melosira (Aulacoseira) italica* def. of spines, sigmoid patt. of punctae	*Aulacoseira italica* (Ehrenb.) Simonsen
Melosira sp.? (Aulacoseira)	unknown	unknown	Melosira? unknown	*Melosira* sp.?
Melosira (Aulacoseira) sp. ?	possibly *Melosira distans var. humilis* or *M. perglabra*	unknown	unknown	*Melosira distans var. humilis* ?

Table 13. Comparison of minimum, maximum and mean metal concentrations (μg/g dry weight) in a sediment core from Sooke Reservoir with mean surface sediment concentrations for 83 Vancouver Island lakes (Rieberger, 1992).

	Vancouver Island mean	**Sooke Reservoir Maximum**	**Sooke Reservoir Minimum**	**Sooke Reservoir Mean**
Aluminum	**19730**	35800	29600	32340
Arsenic	**44.92**	21	10	14
Barium	**79.17**	770	369	464
Cadmium	**1.16**	2	1	1
Calcium	**6750**	11600	8780	10364
Chromium	**36**	47	19	29
Cobalt	**23.94**	44	22	33
Copper	**61.23**	68	52	60
Iron	**30690**	110000	49300	66145
Lead	**39.35**	28	9	12
Magnesium	**49000**	7560	5810	6574
Manganese	**230.7**	49600	3700	14328
Molybdenum	**7.67**	9	1	3
Nickel	**22.73**	98	63	82
Phosphorus	**1301**	3580	1850	2471
Strontium	**34.39**	48	37	44
Vanadium	**55.54**	69	46	56
Zinc	**70.57**	104	61	79

Figures

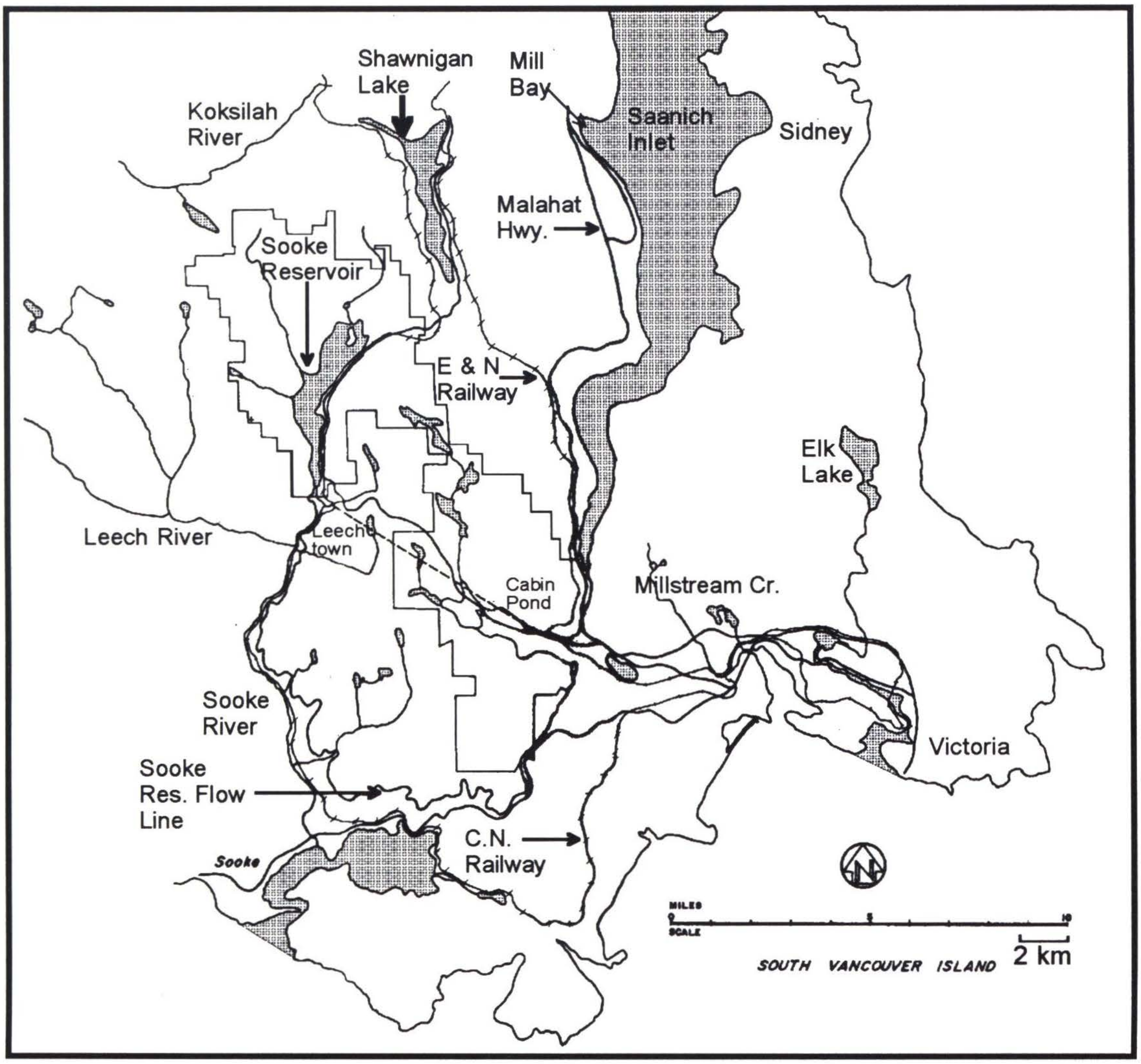
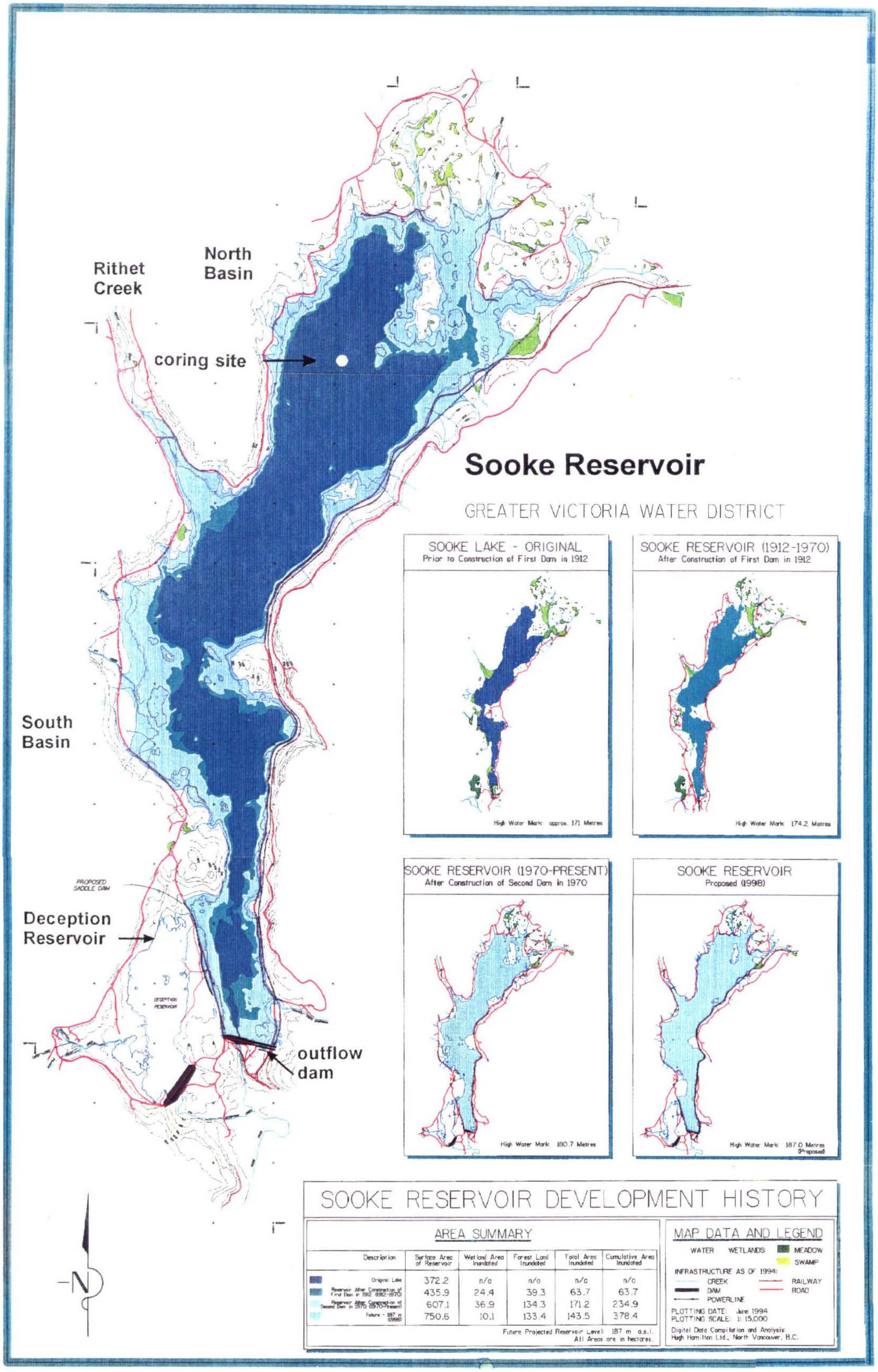


Figure 1. Map of Southern Vancouver Island showing the location of Sooke Reservoir and the G.V.W.D. lands relative to the City of Victoria.

Figure 2. Map of the development history of Sooke Reservoir showing water levels and surface area at four stages of development. The inset contains outlines of the lake as it would have appeared prior to dam construction, following the first dam, following the second dam and as it will appear if future dam construction plans are implemented (modified from map created by Hugh Hamilton Ltd., 1994)



AREA SUMMARY

Description	Surface Area of Reservoir	Wetland Area Inundated	Forest Land Inundated	Total Area Inundated	Cumulative Area Inundated
Original Lake	372.2	n/a	n/a	n/a	n/a
Reservoir After Construction of First Dam in 1912 (1912-1970)	435.9	24.4	39.3	63.7	63.7
Reservoir After Construction of Second Dam in 1970 (1970-Present)	607.1	36.9	134.3	171.2	234.9
Future - 187 m (1998)	750.6	10.1	133.4	143.5	378.4

Future Projected Reservoir Level: 187 m a.s.l.
All Areas are in hectares.

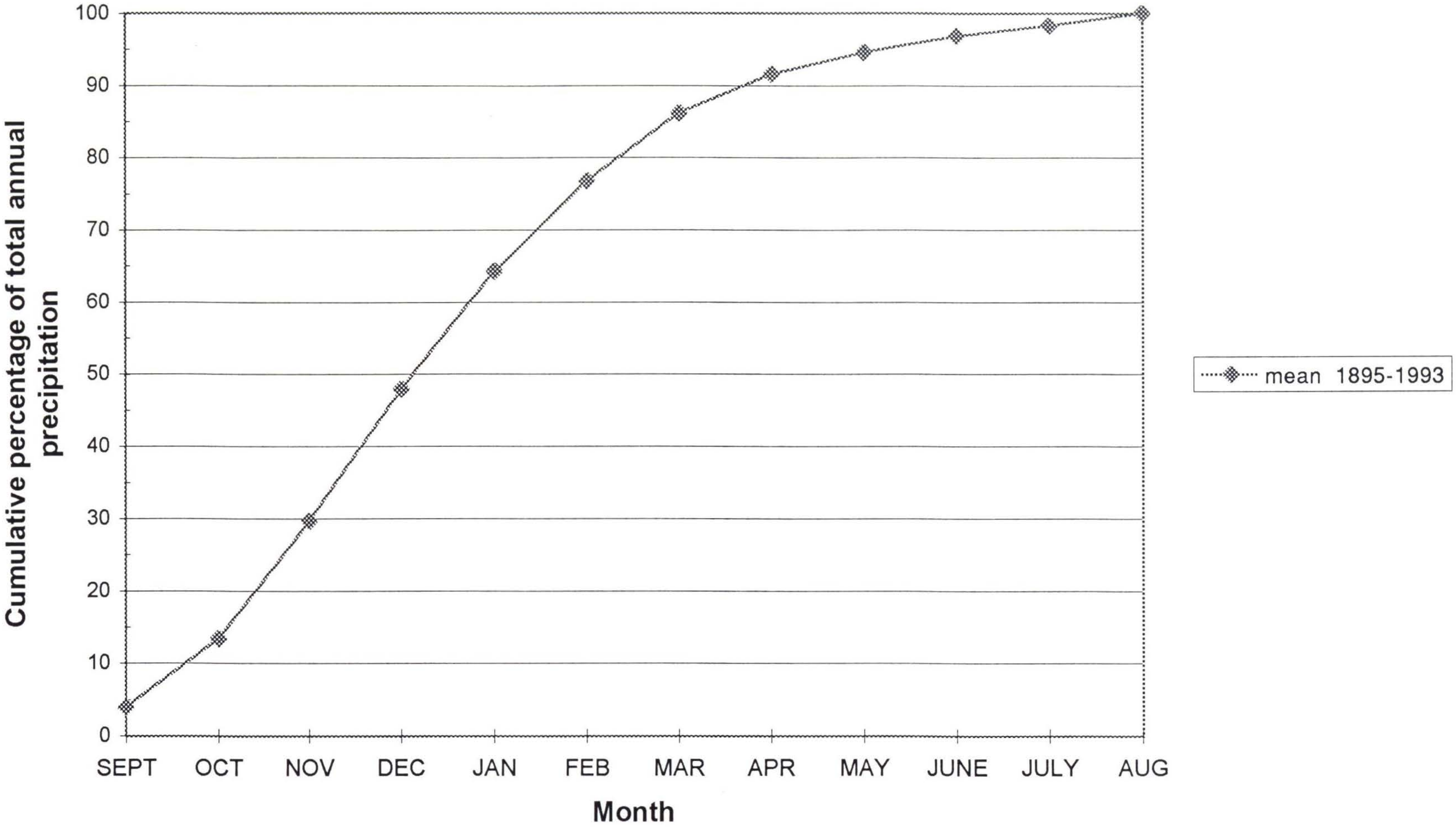
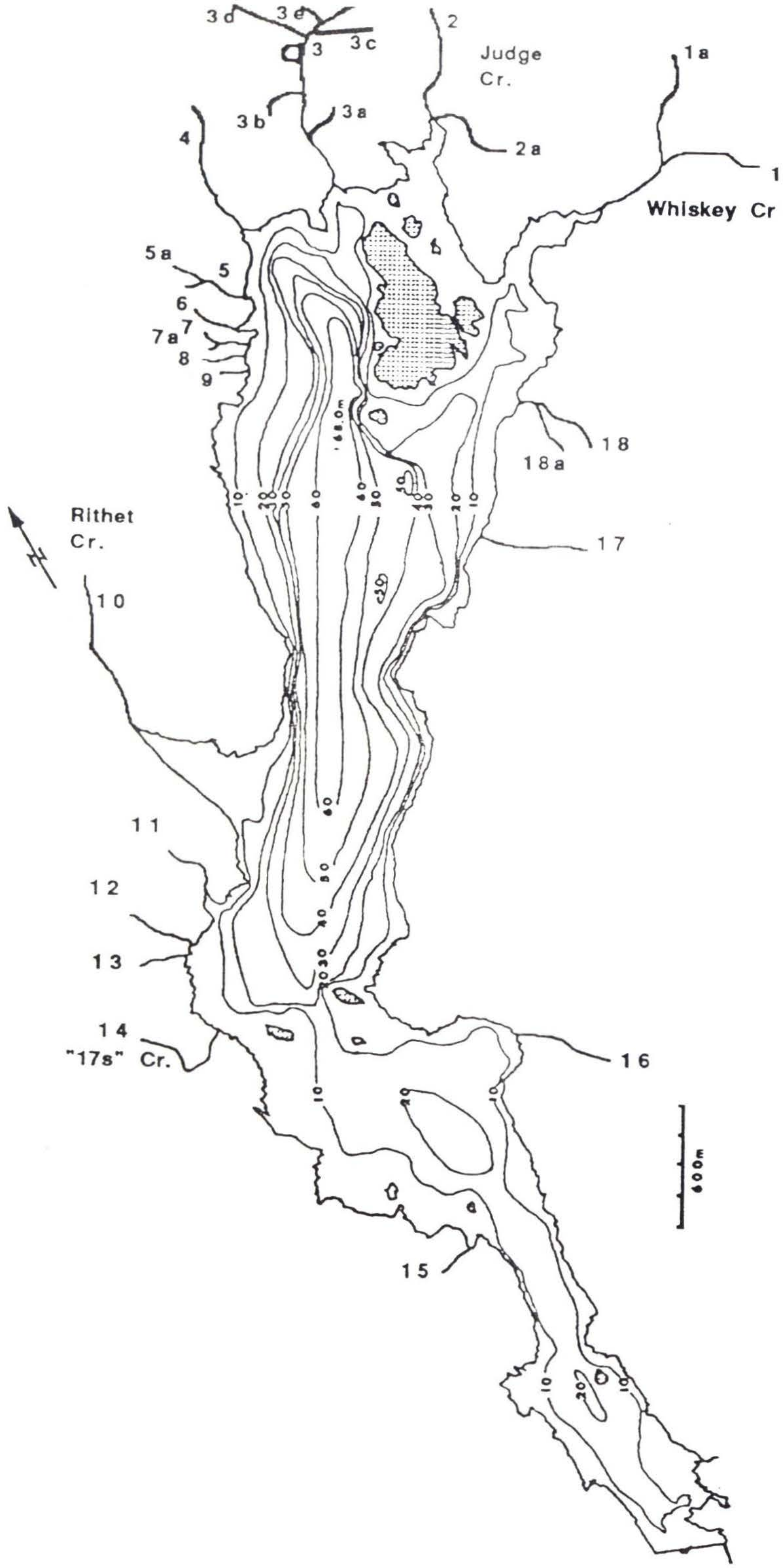


Figure 3. Mean annual cumulative precipitation in the Sooke Watershed between 1895 and 1993.

Figure 4. Bathymetric map of Sooke Reservoir (depths in metres) following construction of the second dam in 1970 including tributary streams. Numbers correspond to those assigned by Axys (1994) during the environmental impact study of the proposed Sooke Reservoir expansion.


3d
3e
3
3c
2
Judge Cr.
1a
3b
3a
4
2a
1
Whiskey Cr
5a
5
6
7
7a
8
9
168.0m
18
18a
10
20
30
40
60
Rithet Cr.
N
10
17
11
12
13
14
"17s" Cr.
16
15
600m

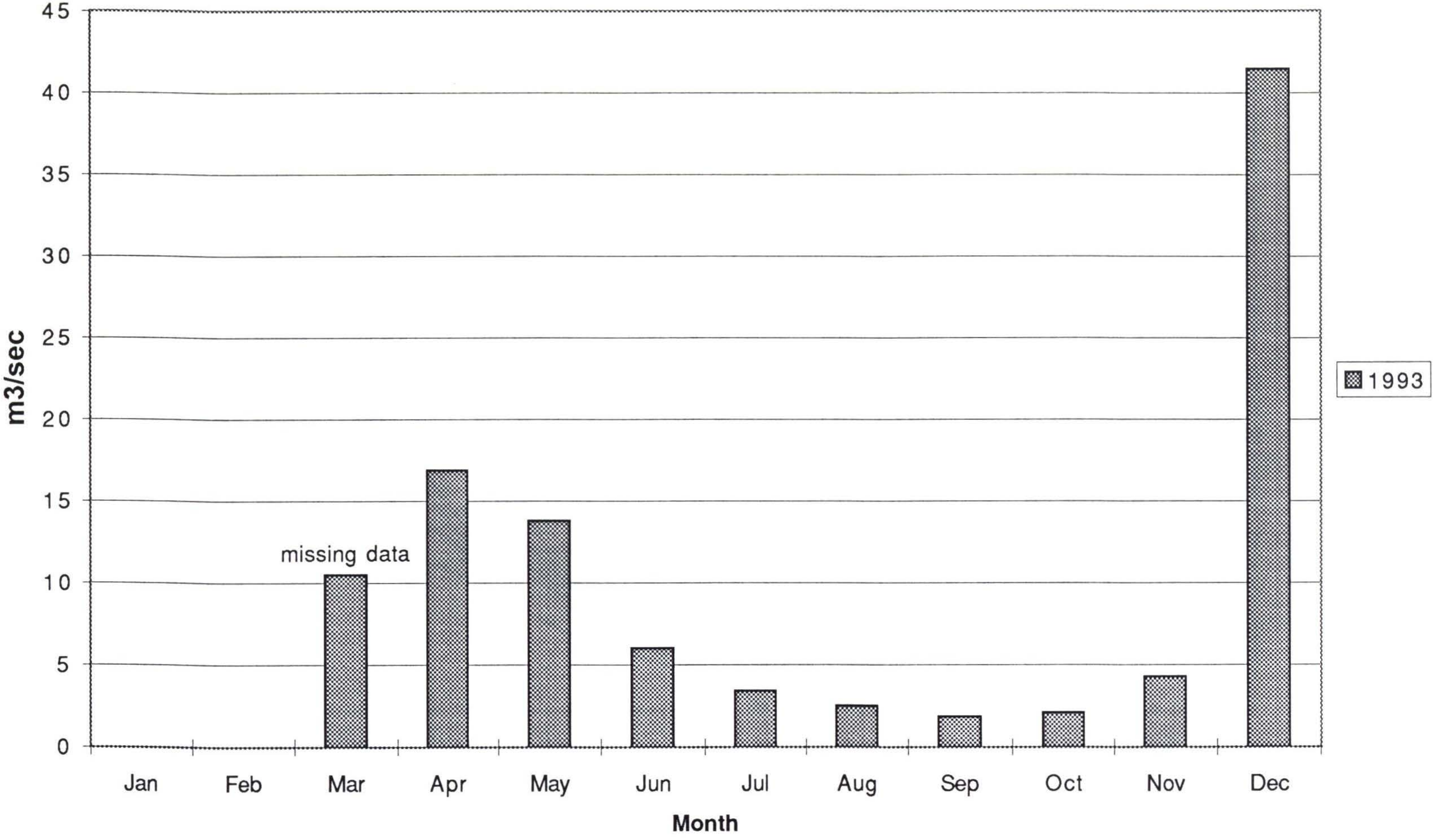


Figure 5. Rithet Creek annual discharge for the year 1993 in m3/second. Data for January, February and part of March are unavailable.

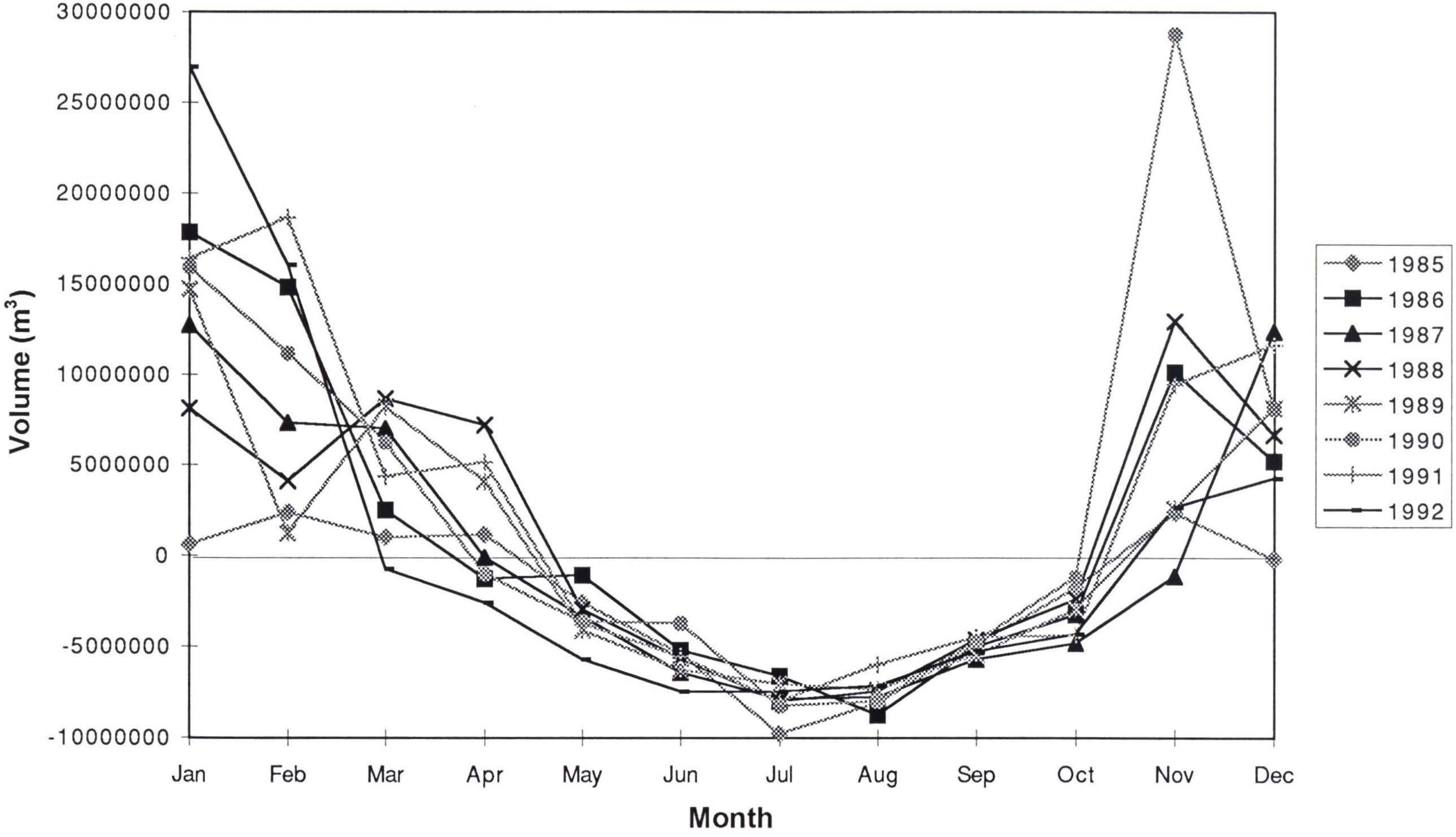


Figure 6. Sooke Reservoir net inflow (m^3) 1985-1992, calculated from reservoir water height and consumption values (source: G.V.W.D.). The volume of water consumed by fisheries and diversion into the Charters Reservoir is not included.

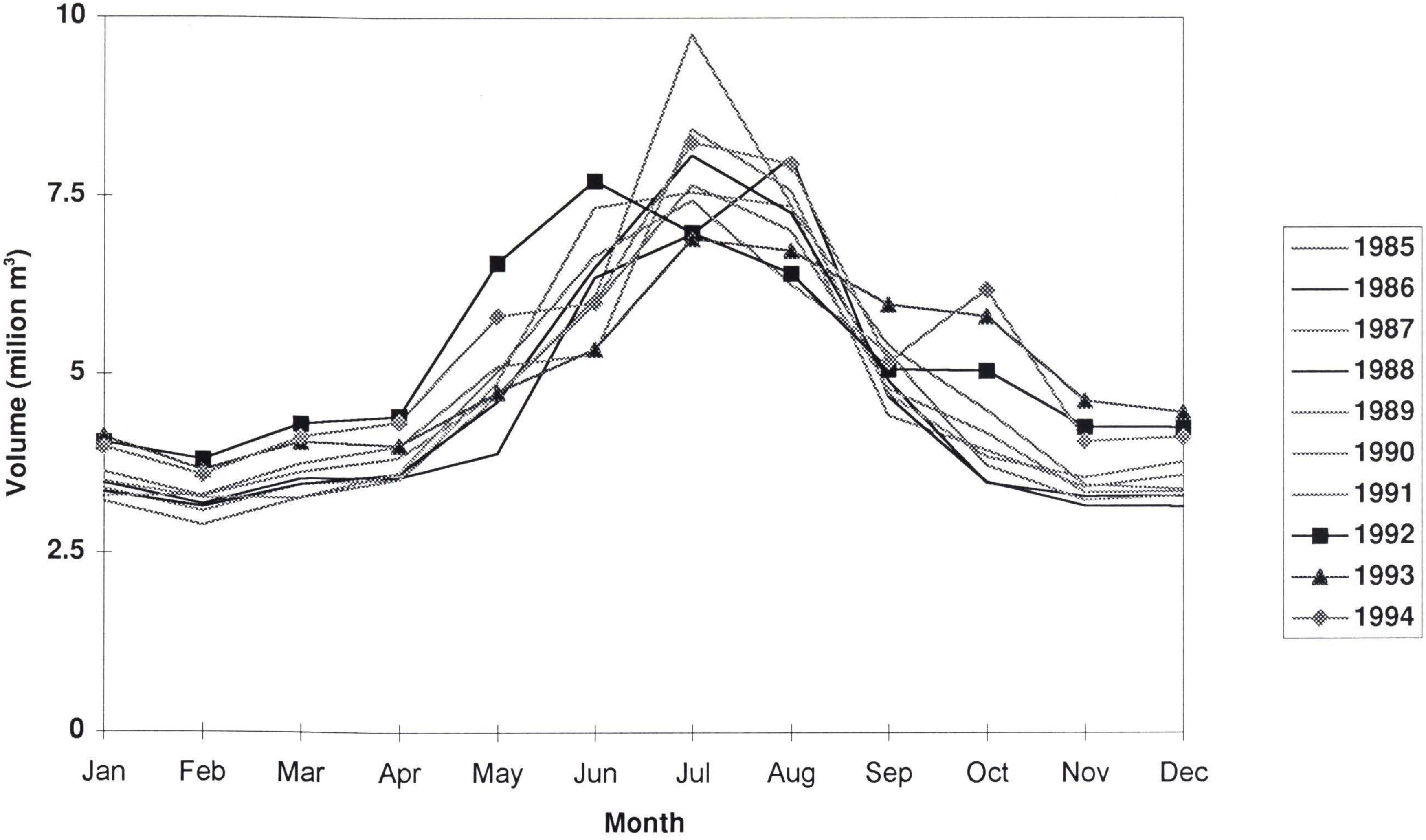
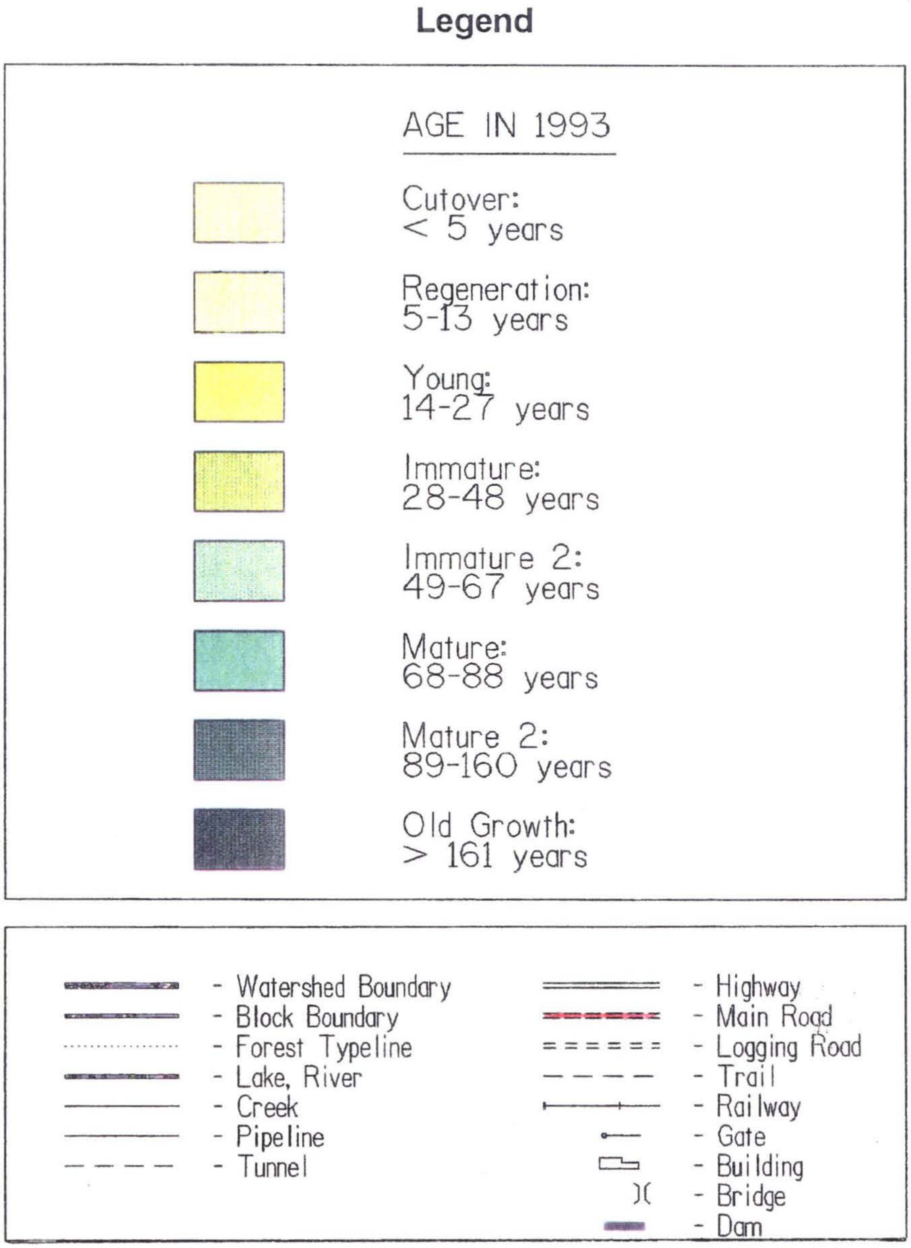


Figure 7. Sooke Reservoir monthly discharge 1985-1994 in millions of cubic metres. 1992-1994 values include the volume spilled for fisheries purposes whereas this is excluded for 1985-1991.

Figure 8. The farm at Sooke Lake Narrows (the "Daisy Patch") c. 1885. The house was rafted to the south end of Sooke Reservoir prior to the construction of the dam and used as a caretaker's house. Photo courtesy of B.C. Archives and Records Services.


Sooke Lake

Figure 9. Map of age-classes of forest stands within the Sooke Watershed (1993) showing main roads and landmarks. Modified from a map produced by Hugh Hamilton Ltd., North Vancouver, B.C.



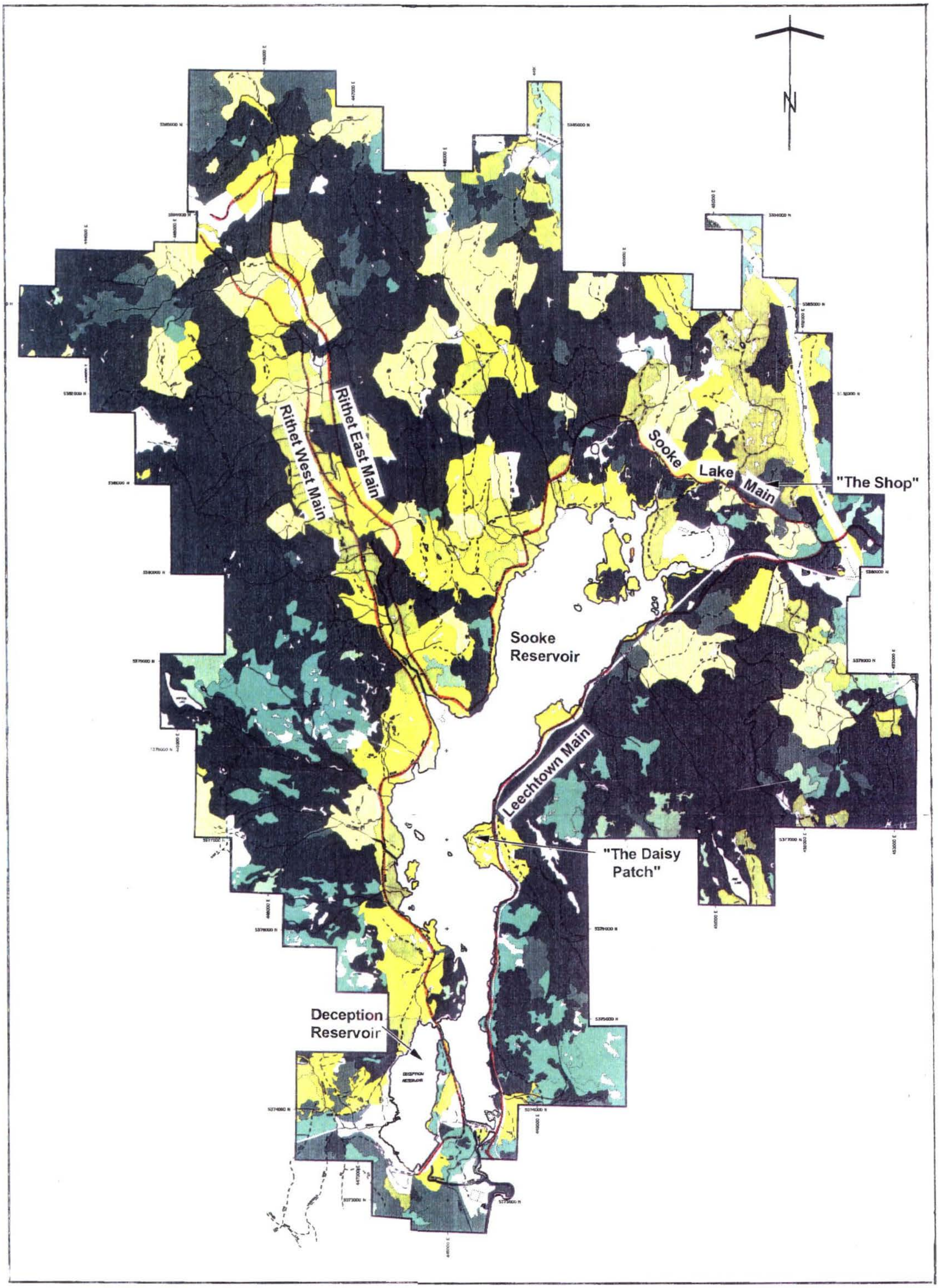

N
Rithet West Main
Rithet East Main
Sooke
Lake
Main
"The Shop"
Sooke
Reservoir
Leechtown Main
"The Daisy
Patch"
Deception
Reservoir
DECEPTION
RESERVOIR

Figure 10. Photograph of Sooke flowline construction near the newly-created Humpback Reservoir. July 6, 1914. Photo courtesy of Mr. H. Melville.

Concrete Pipe Line Near Humpback
7-6-14.

Figure 11. Opening ceremony for the new reservoir in 1913. Dignitaries are standing on the intake tower at the south end of the reservoir. Photo courtesy of B.C. Archives and Records Services.

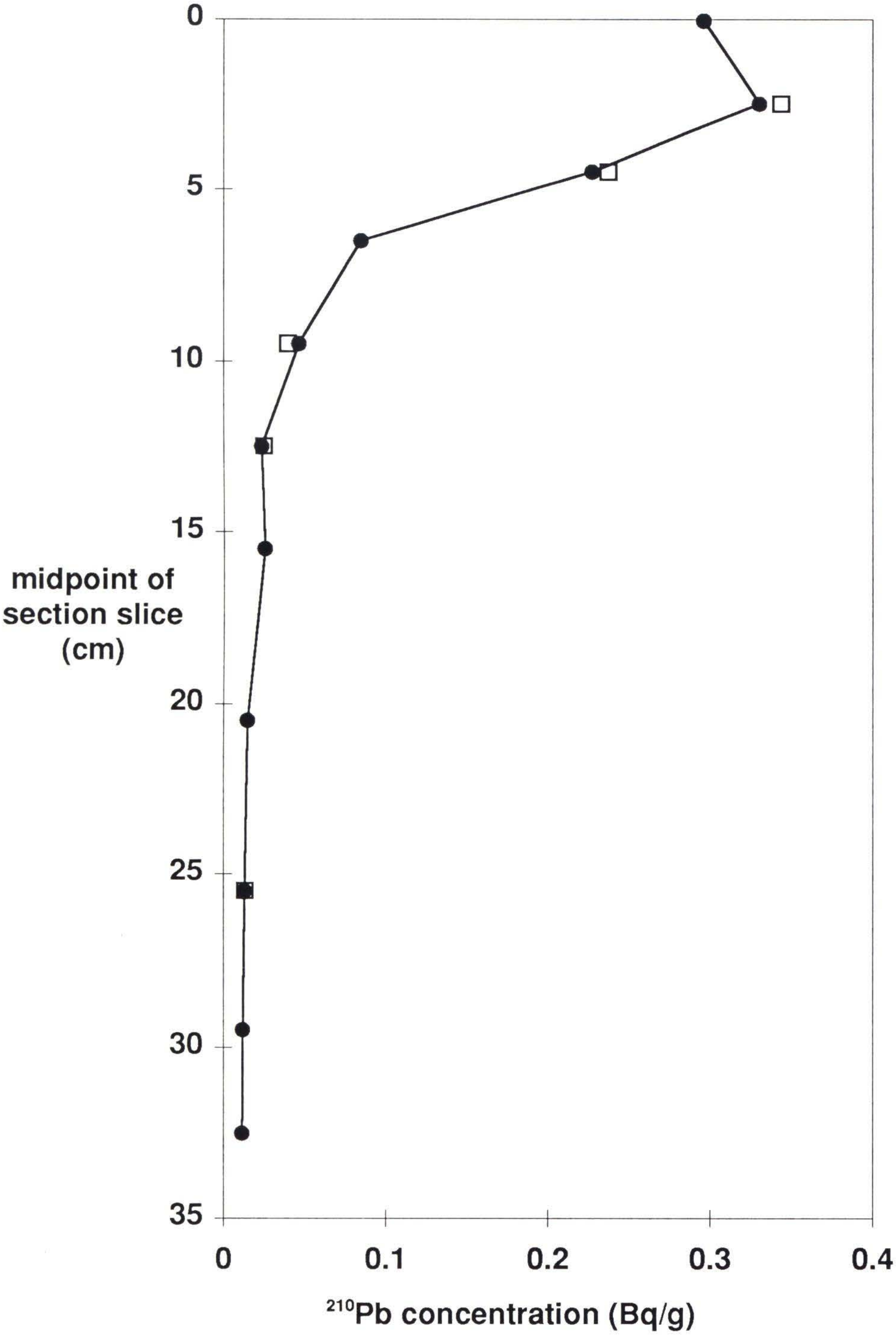


Figure 12. Decay corrected ^{210}Pb profile for the North Basin of Sooke Reservoir. Squares denote samples analysed in duplicate.

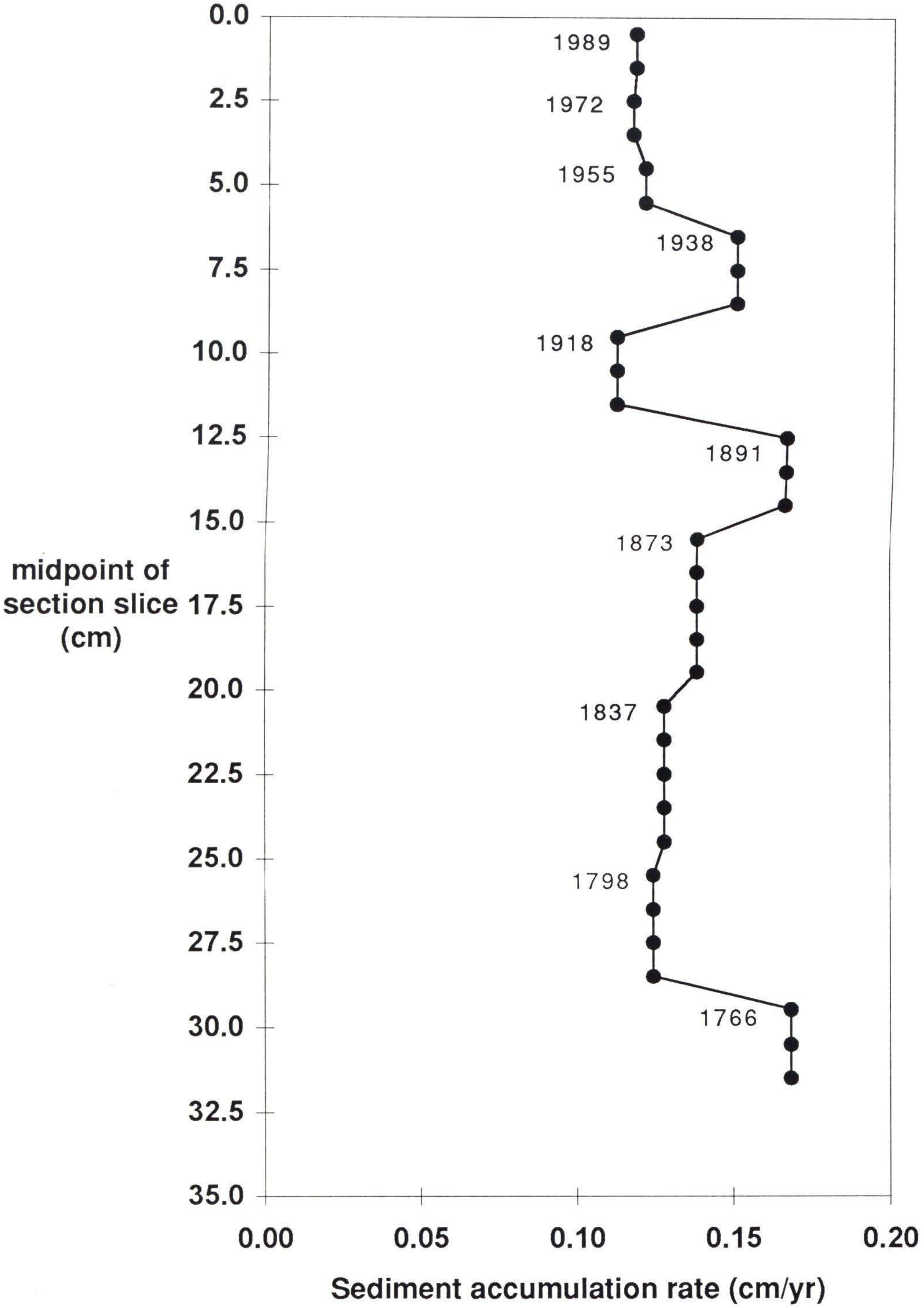
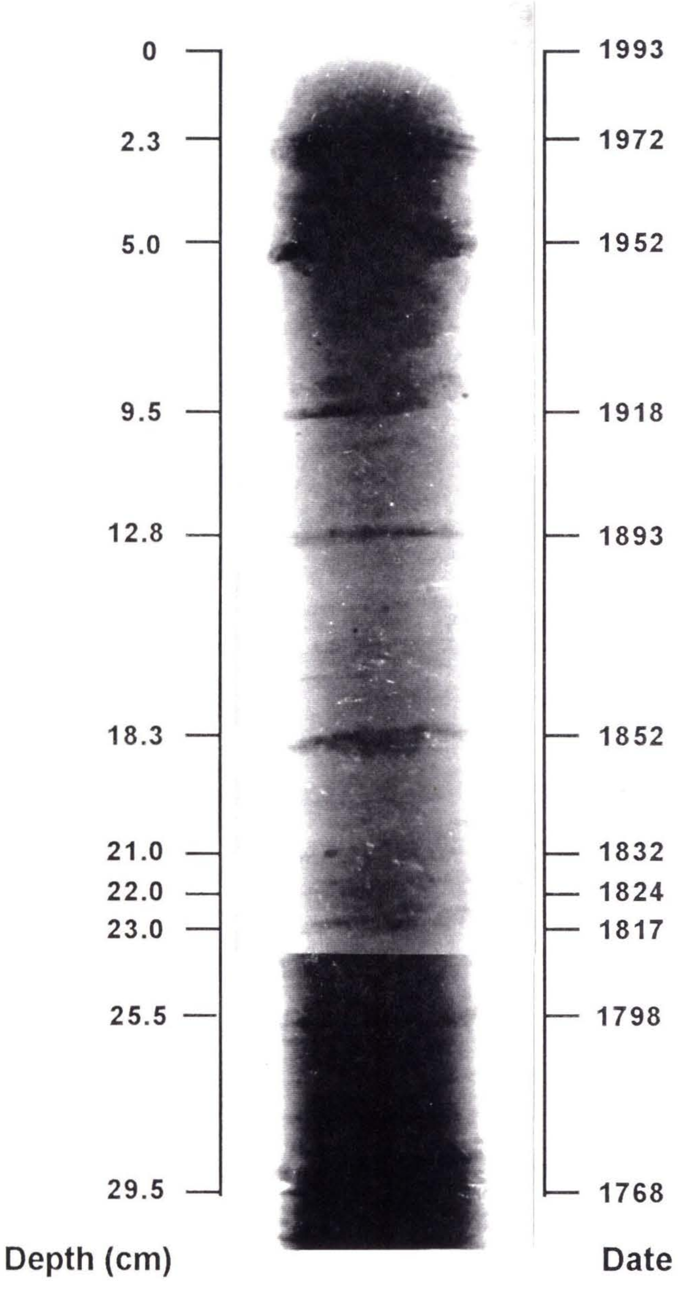


Figure 13. Sediment accumulation rate (SAR) in cm/yr for the North Basin of Sooke Reservoir as calculated using the C.I.C. model.

Figure 14. Photographic print of north basin sediment core X-ray. Core was taken in May 1994. Note that bands of higher density appear light on the original x-ray and dark on the photograph. Actual depths in cm are marked on the left axis. Estimated dates are marked on the right axis.


0
2.3
5.0
9.5
12.8
18.3
21.0
22.0
23.0
25.5
29.5
Depth (cm)
1993
1972
1952
1918
1893
1852
1832
1824
1817
1798
1768
Date

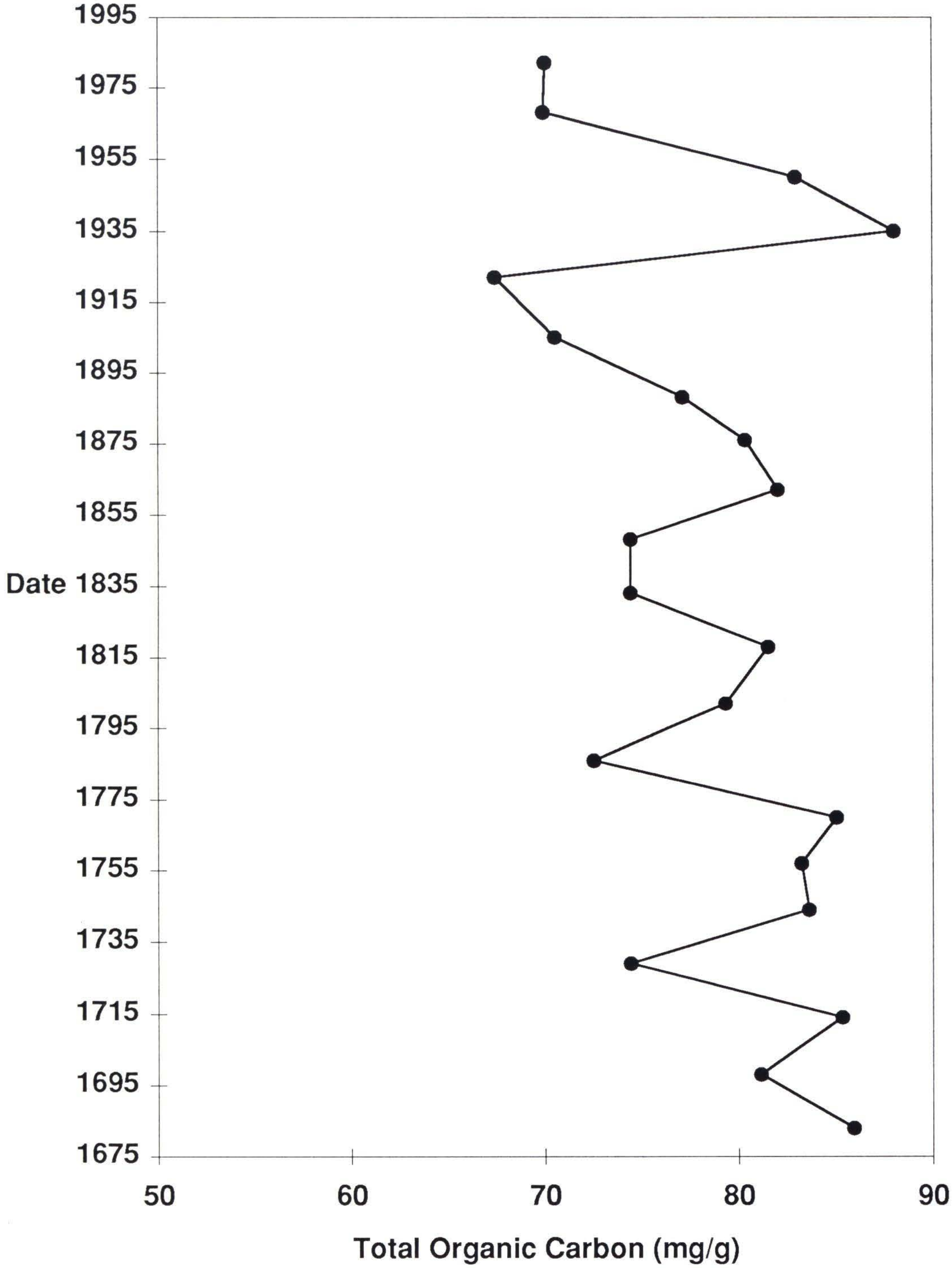


Figure 15. Total organic carbon concentration (mg/g) over time. Core was taken in January 1993 from the North Basin of Sooke Reservoir.

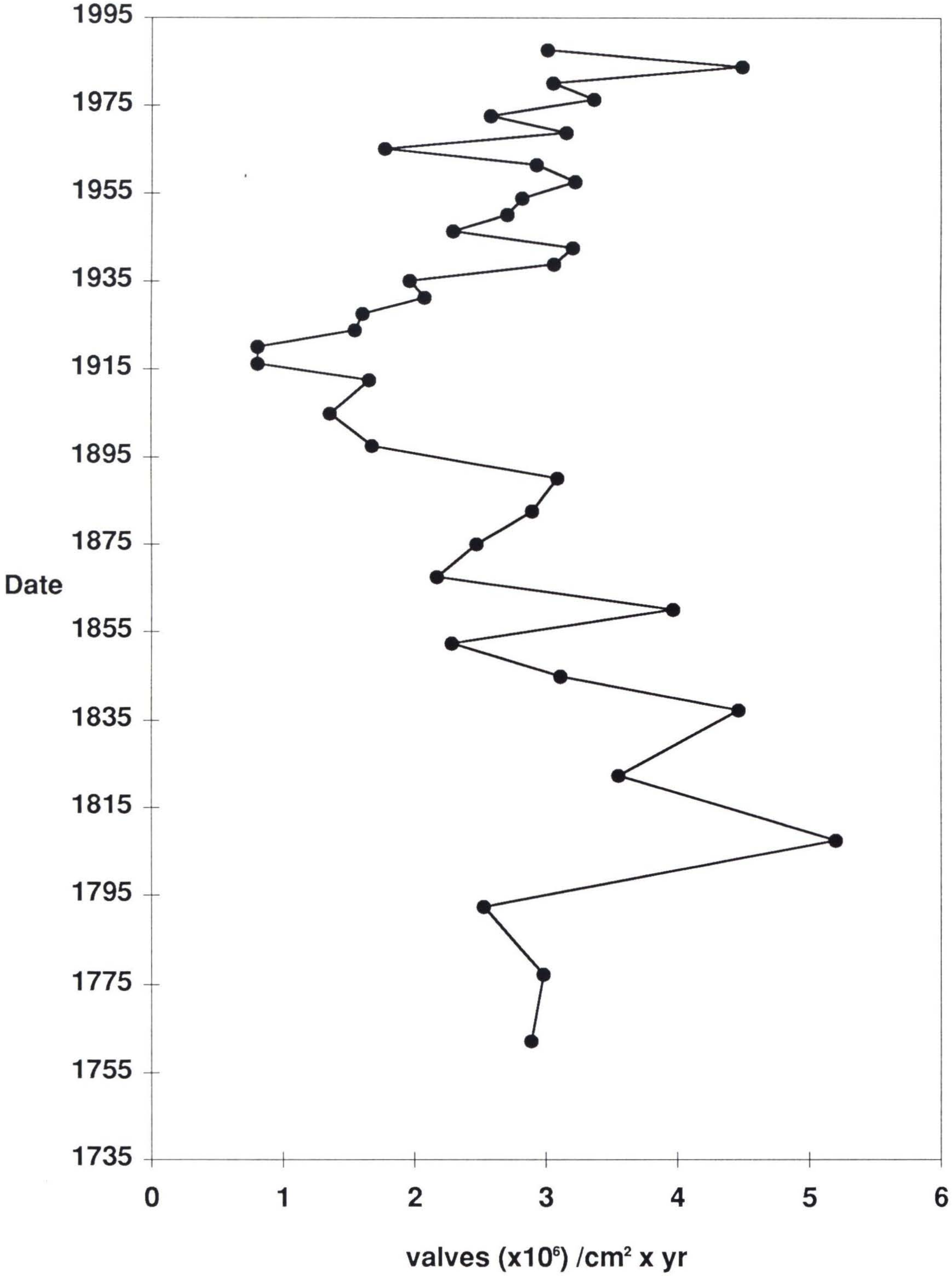


Figure 16. Millions of diatom valves per year deposited over a 1 square centimetre area of the sediment in Sooke Reservoir between 1758 and 1993.

Figure 17. Scanning electron micrographs of four centric diatom species from Sooke Reservoir: a) *Cyclotella bodanica* b) *Cyclotella ocellata* c) *Stephanodiscus alpinus* ?d) *Stephanodiscus astraea*.

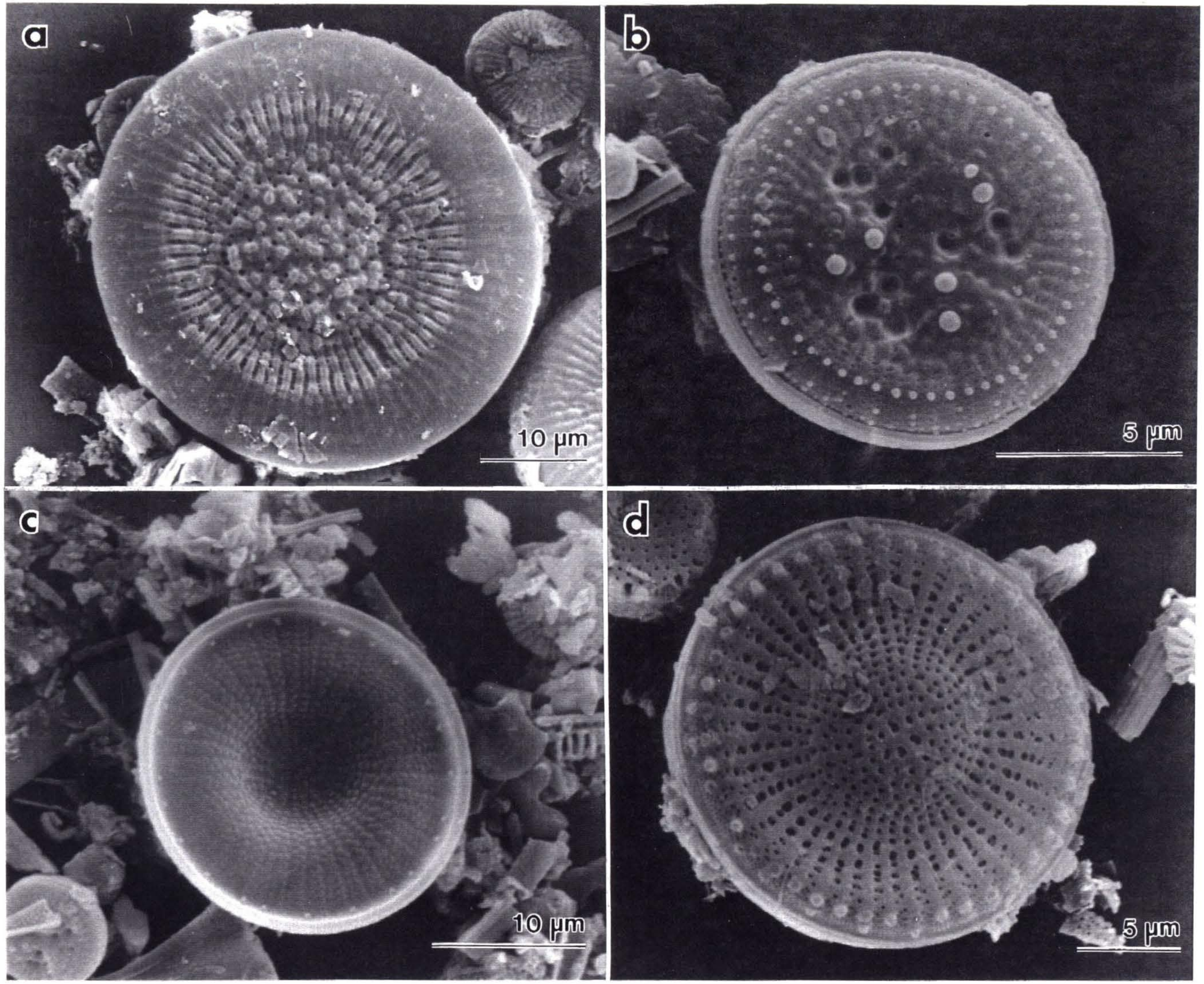

a
10 µm
b
5 µm
c
10 µm
d
5 µm

Figure 18. Scanning electron micrographs of two centric diatom species from Sooke Reservoir: a) *Cyclotella stelligera* b) *Cyclotella michiganiana* c) *Cyclotella stelligera*, full valve view d) *Cyclotella michiganiana*, view of inner epitheca.

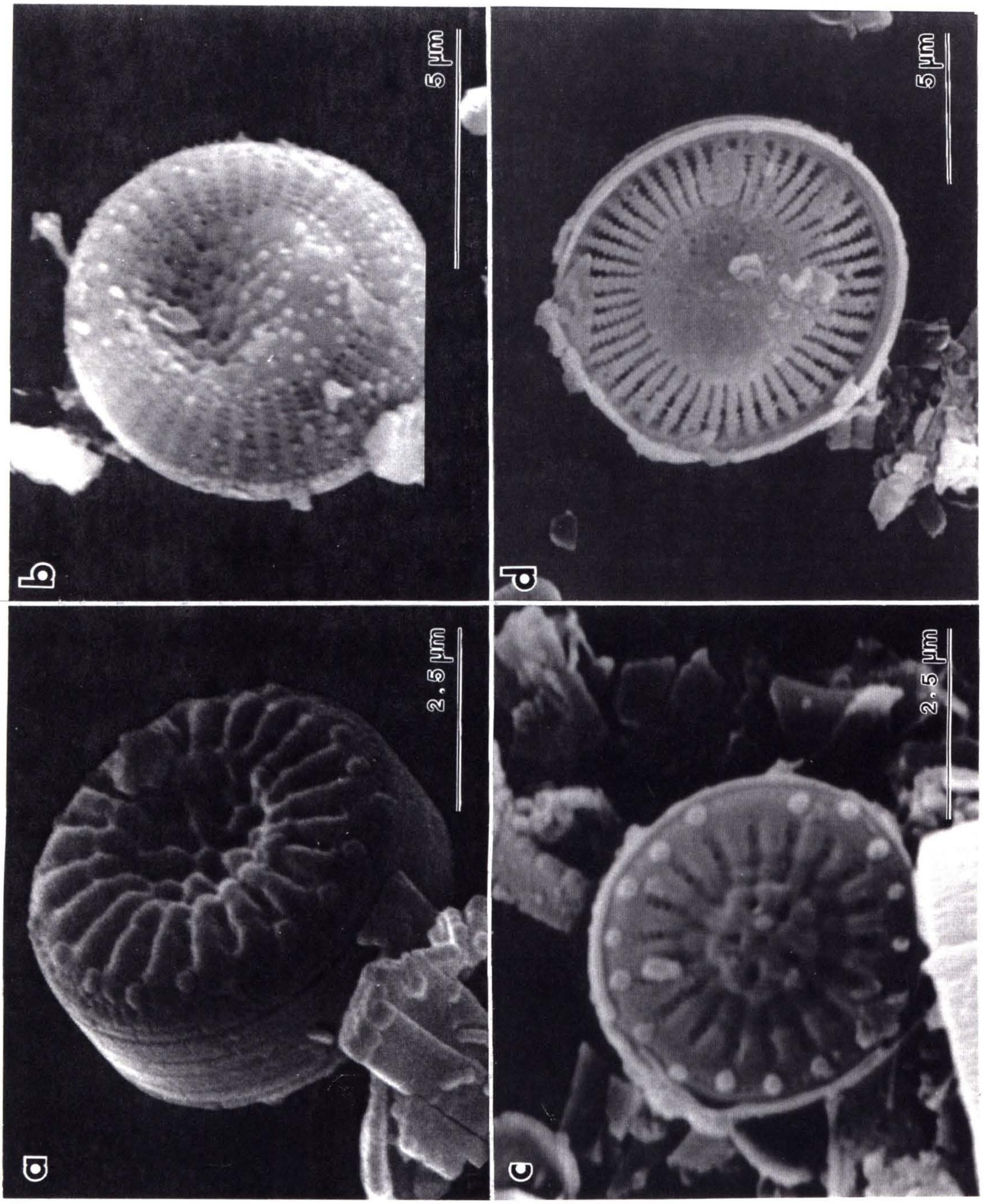
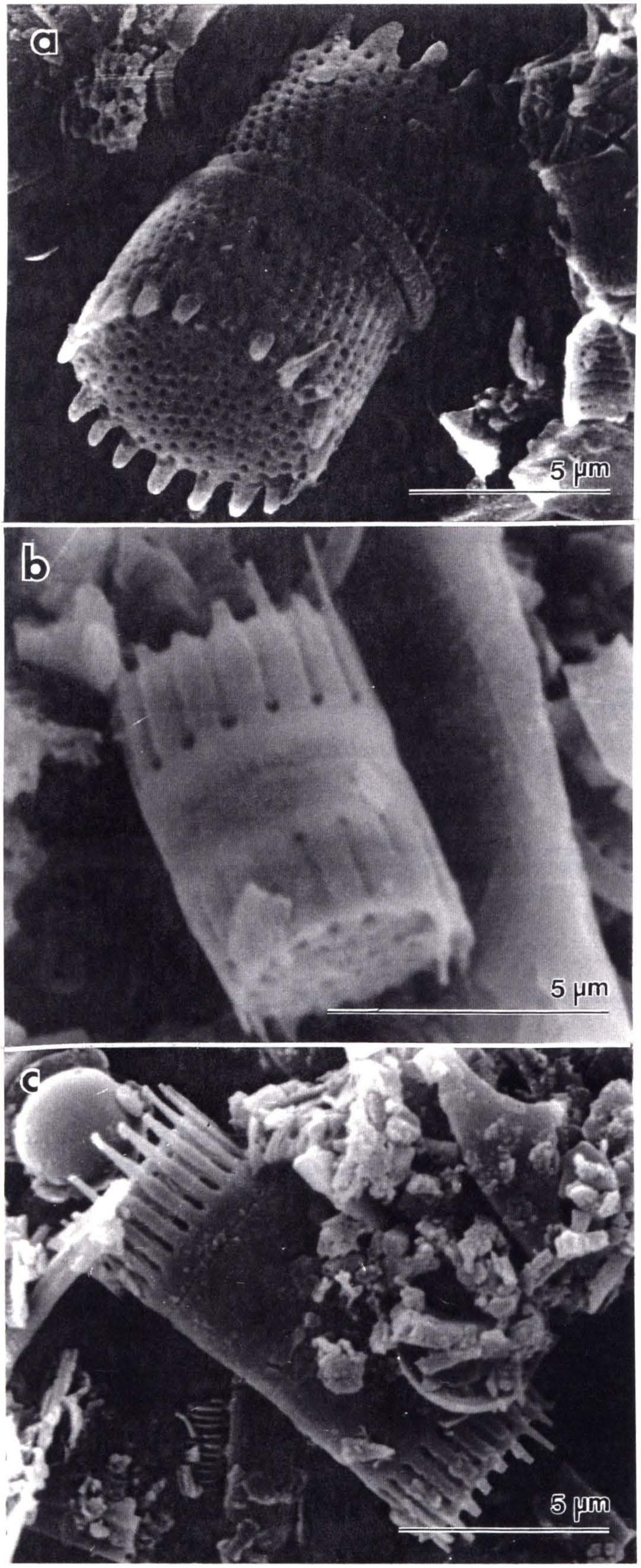

a
2,5 µm
b
5 µm
c
2,5 µm
d
5 µm

Figure 19. Scanning electron micrographs of three centric diatom species from Sooke Reservoir: a) *Aulacoseira italica* b) *Aulacoseira sp.?* c) unknown– thought to belong to the genus *Aulacoseira*. *Copies* of these photographs were sent to outside experts for taxonomic verification of the species.


a
5 µm
b
5 µm
c
5 µm

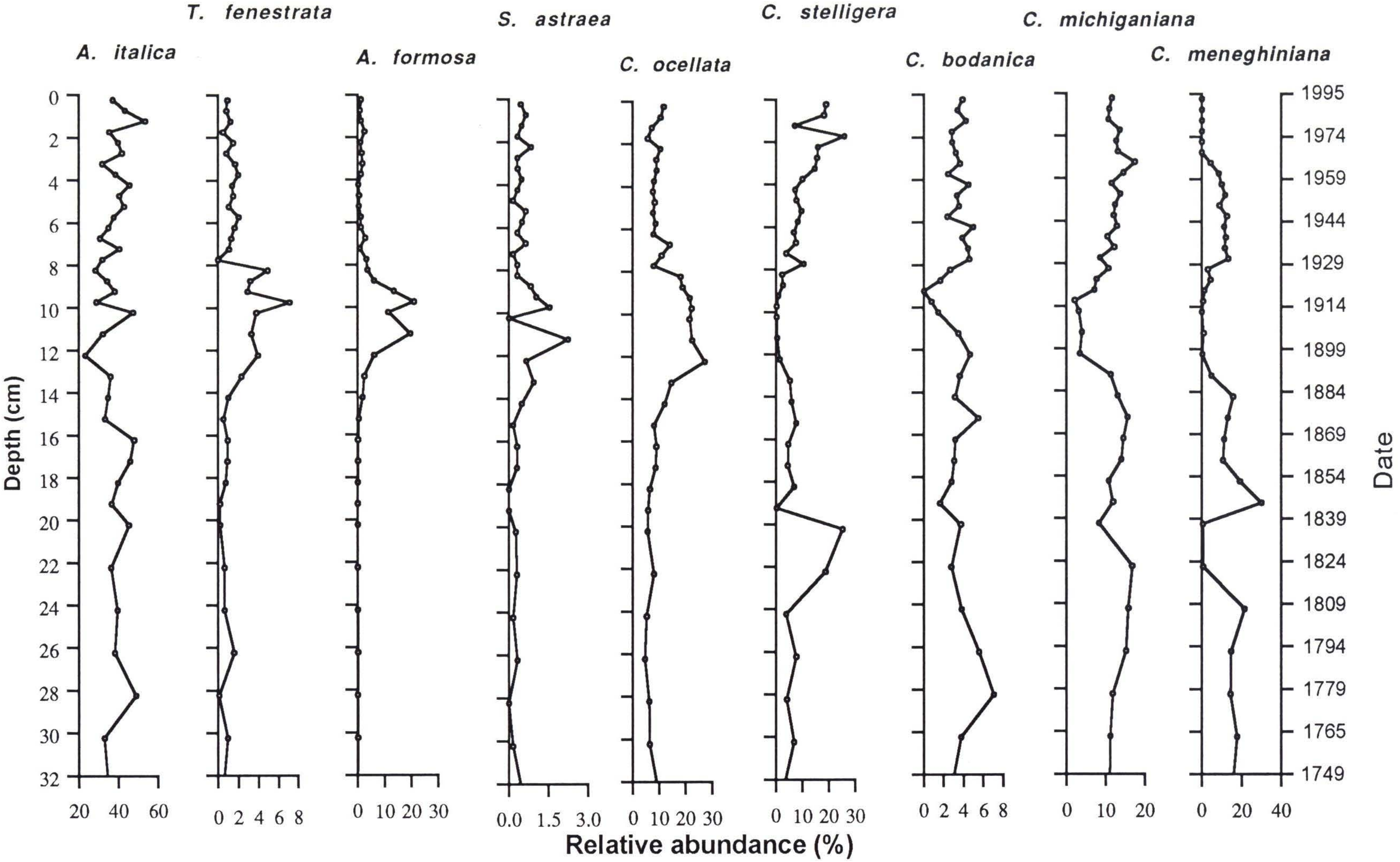


Figure 20. Relative abundances of the nine dominant diatom species with depth. Calculated dates are marked on the Y-axis at the right.

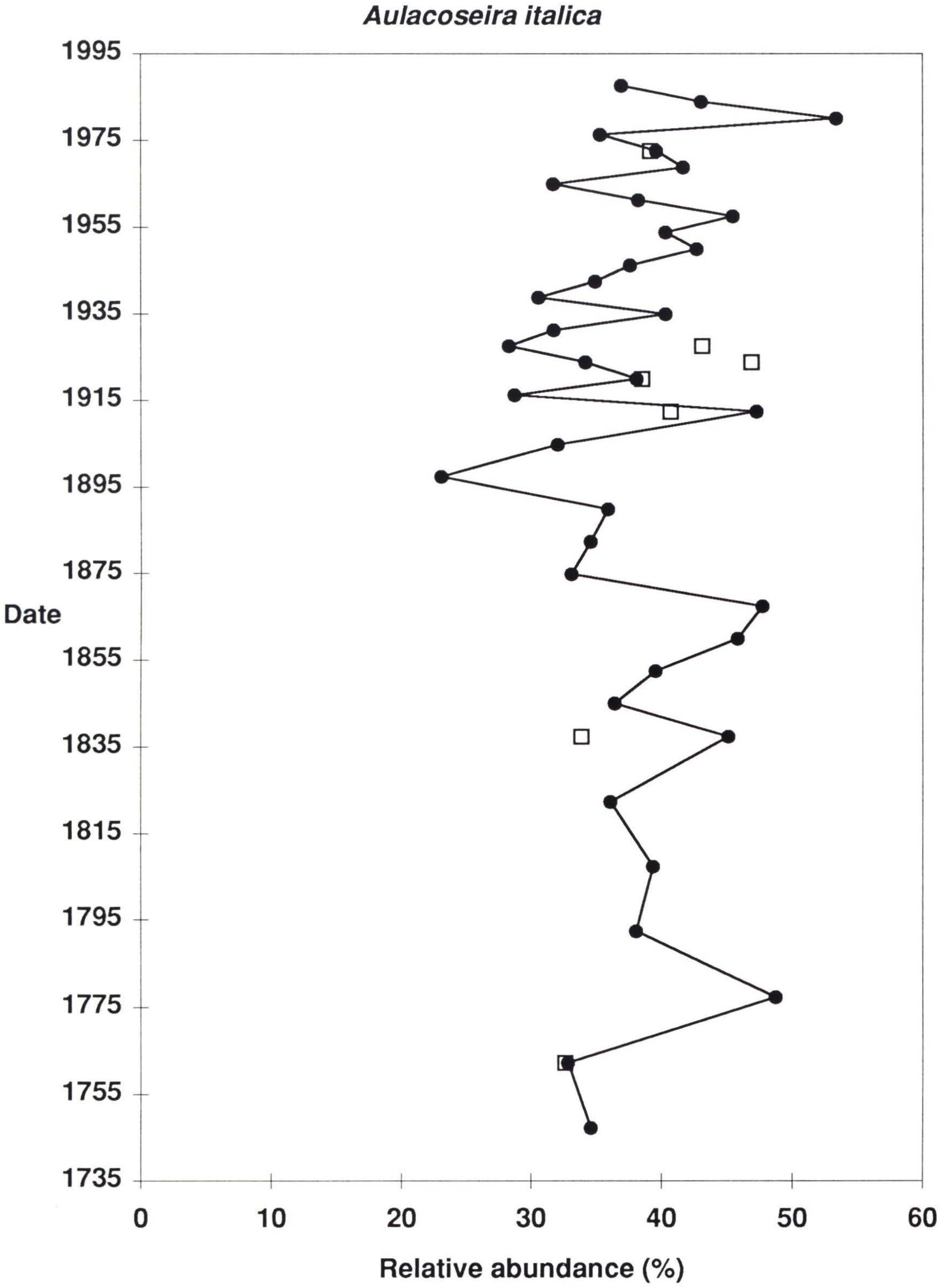


Figure 21. Relative abundance of *Aulacoseira italica* over time. Circles show samples from core #7, open squares show samples from core #8.

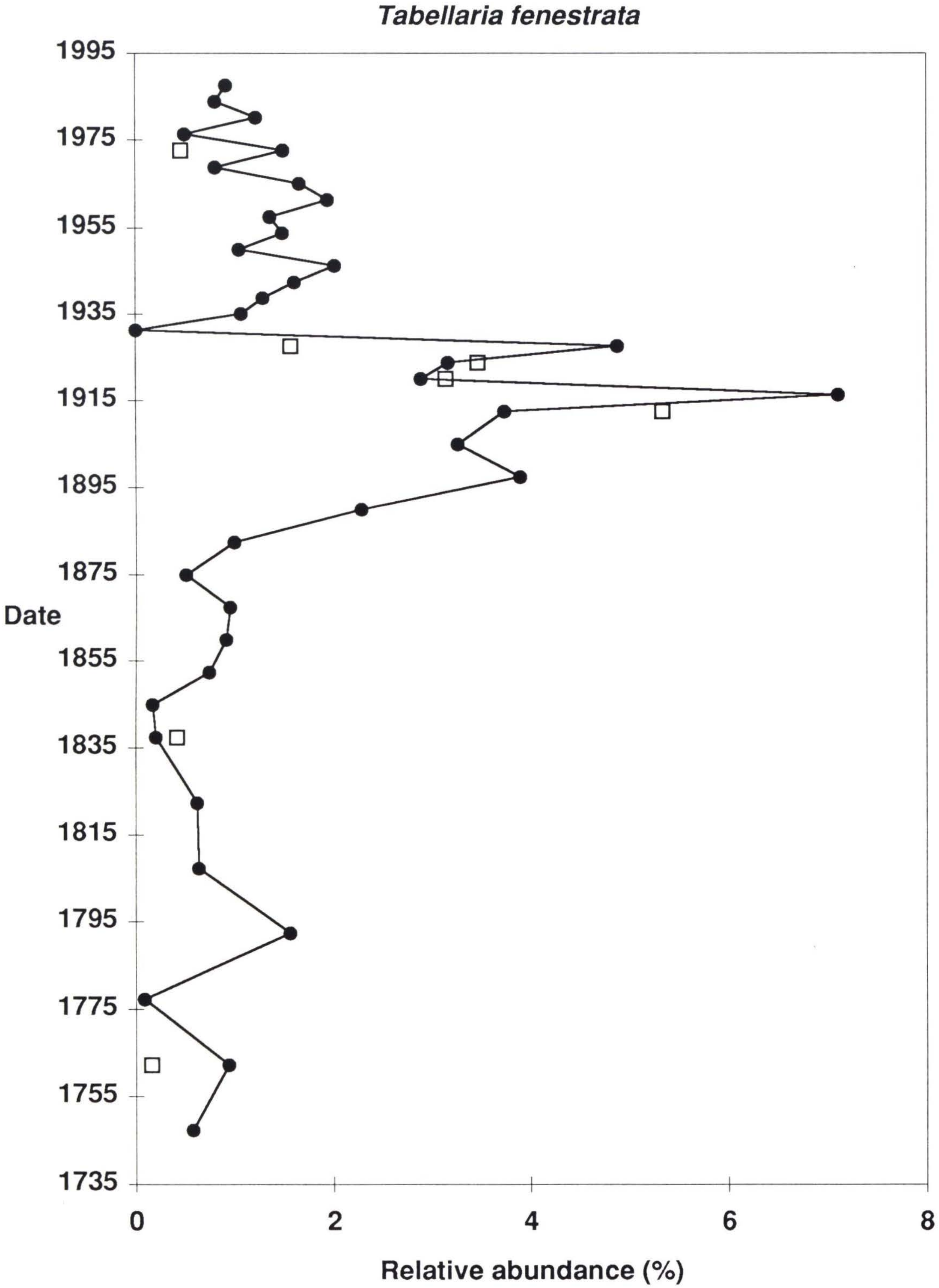


Figure 22. Relative abundance of *Tabellaria fenestrata* over time. Circles show samples from core #7, open squares show samples from core #8.

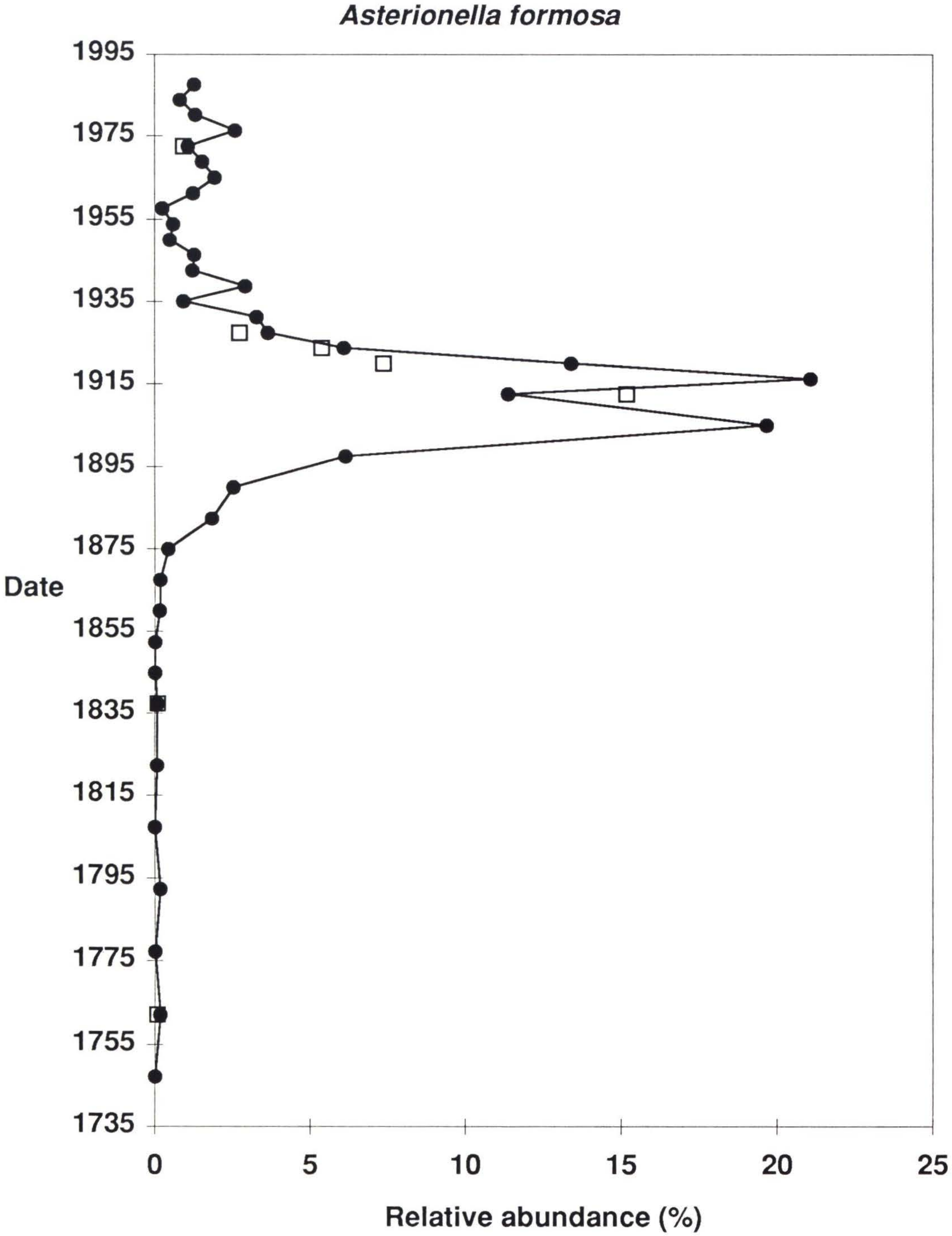


Figure 23. Relative abundance of *Asterionella formosa* over time. Circles show samples from core #7, open squares show samples from core #8.

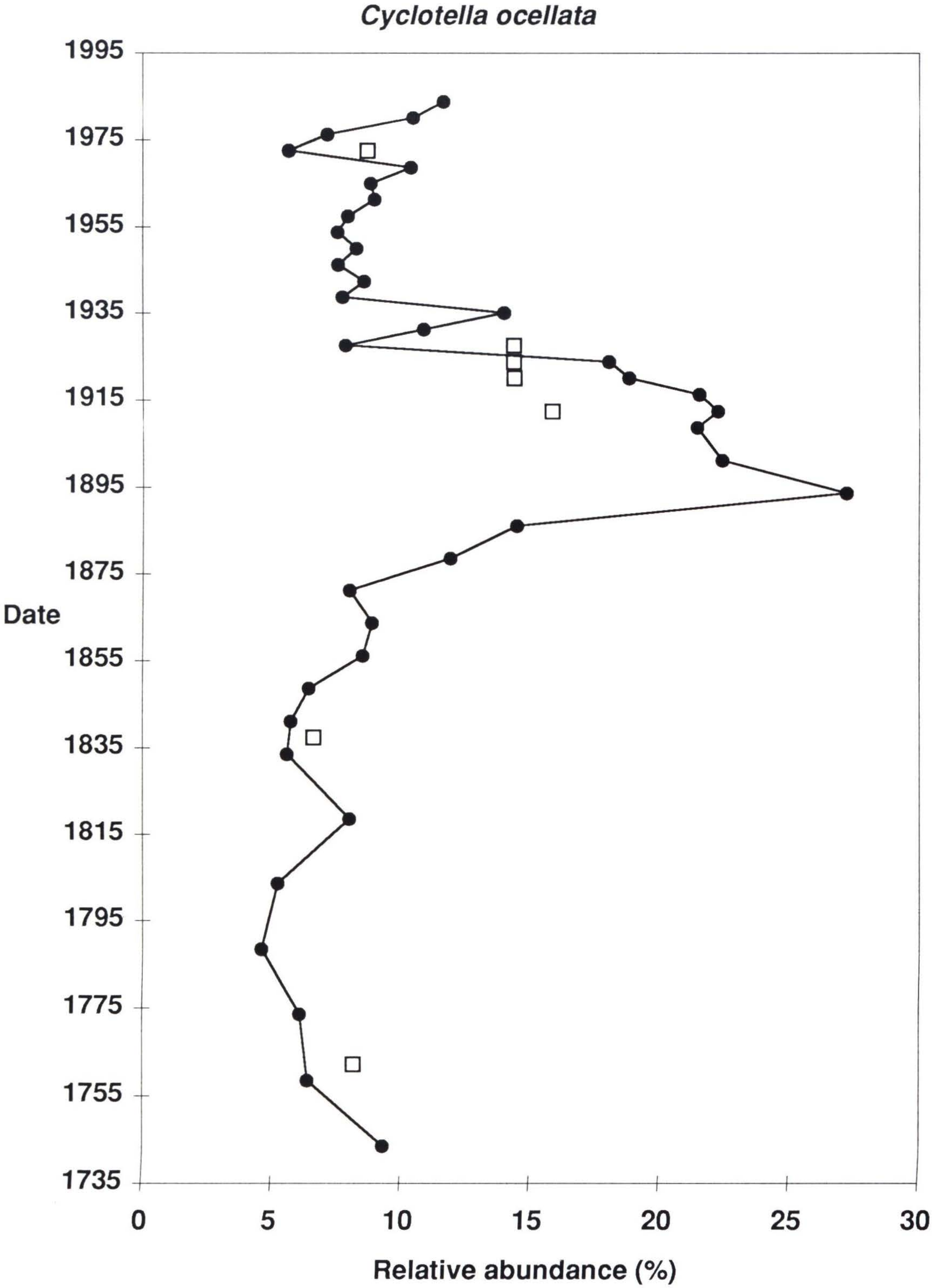


Figure 24. Relative abundance of *Cyclotella ocellata* over time. Circles show samples from core #7, open squares show samples from core #8.

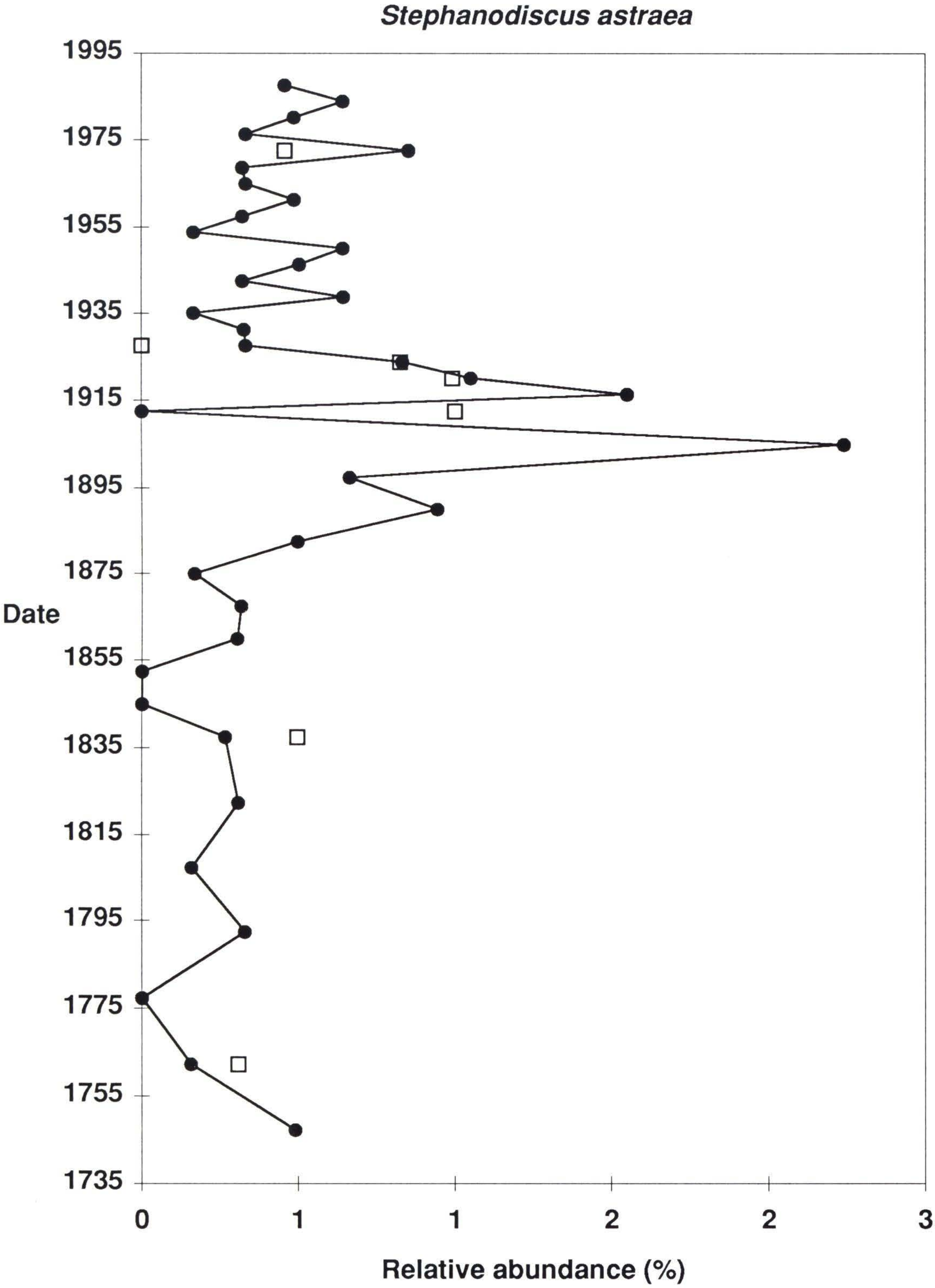


Figure 25. Relative abundance of *Stephanodiscus astraea* over time. Circles show samples from core #7, open squares show samples from core #8.

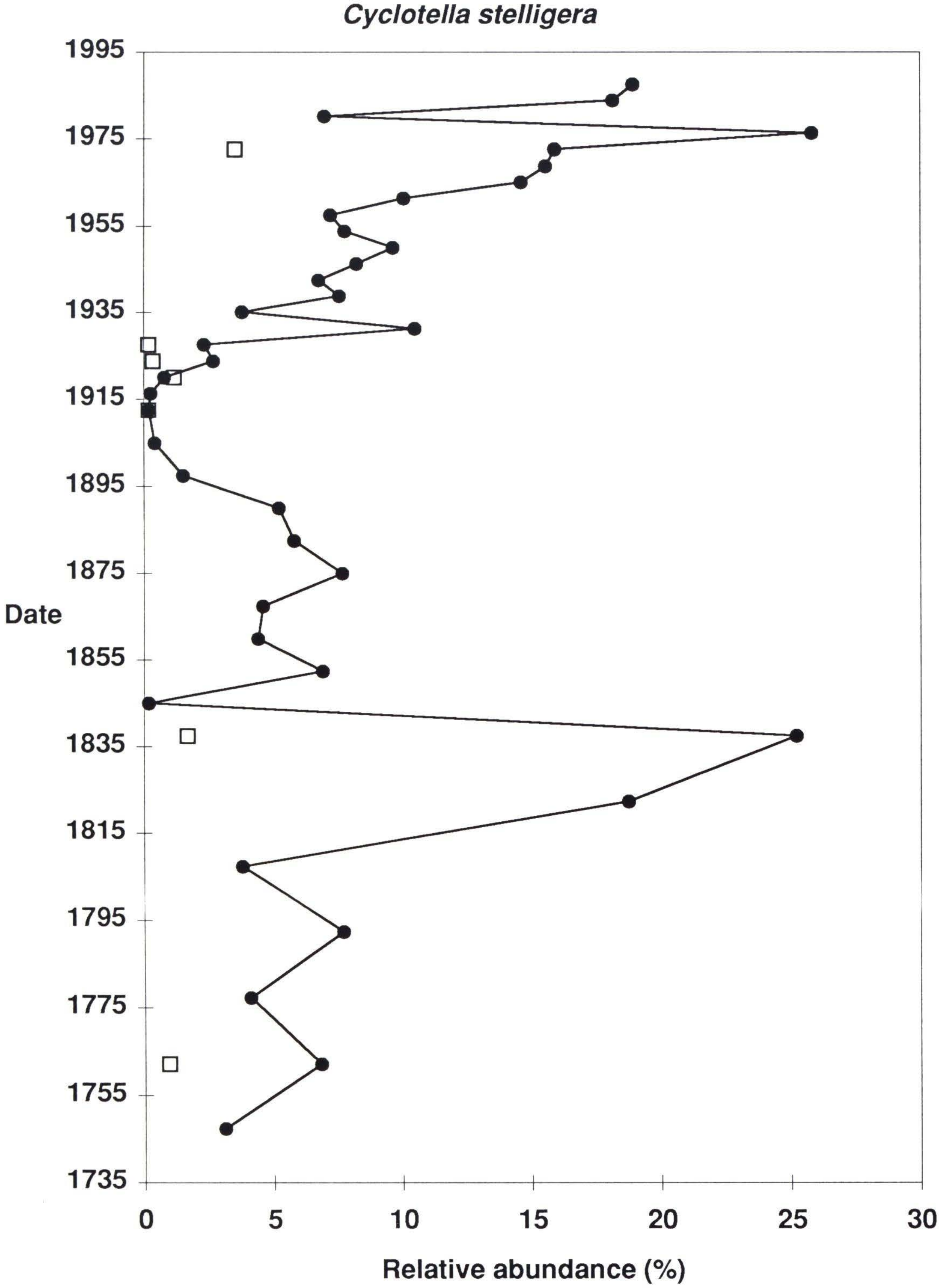


Figure 26. Relative abundance of *Cyclotella stelligera* over time. Circles show samples from core #7, open squares show samples from core #8.

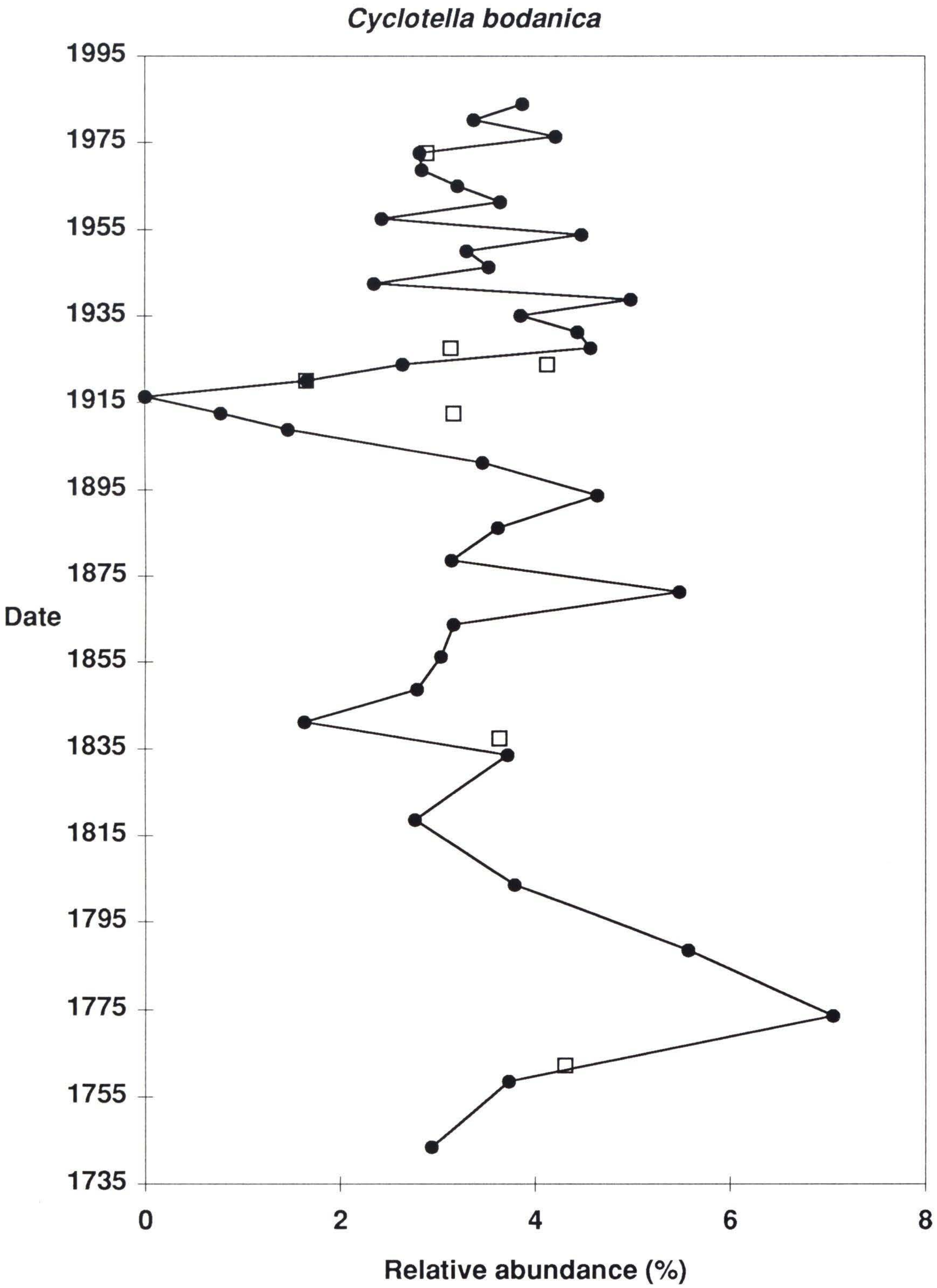


Figure 27. Relative abundance of *Cyclotella bodanica* over time. Circles show samples from core #7, open squares show samples from core #8.

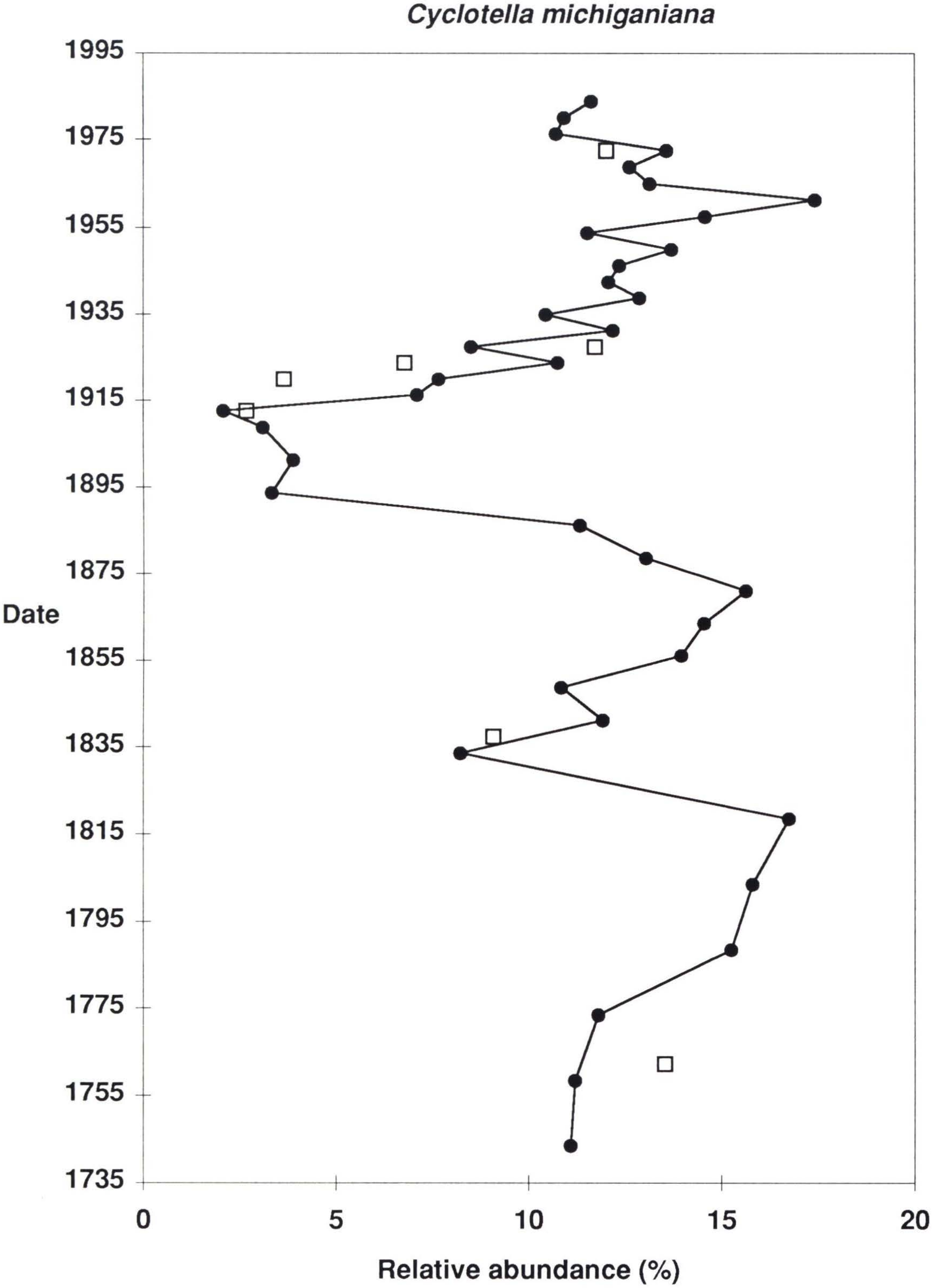


Figure 28. Relative abundance of *Cyclotella michiganiana* over time. Circles show samples from core #7, open squares show samples from core #8.

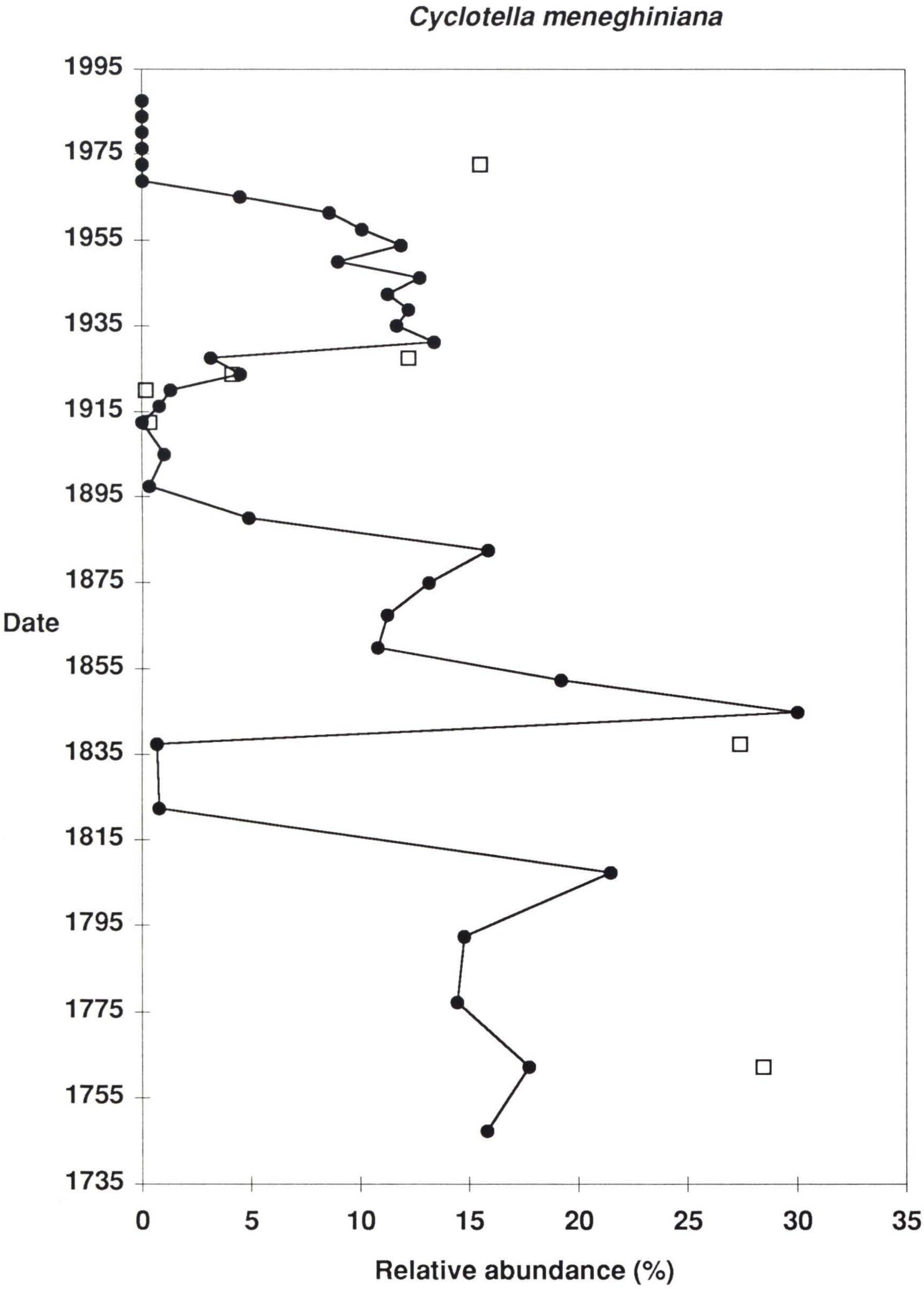


Figure 29. Relative abundance of *Cyclotella meneghiniana* over time. Cirlces show samples from core #7, open squares show samples from core #8.

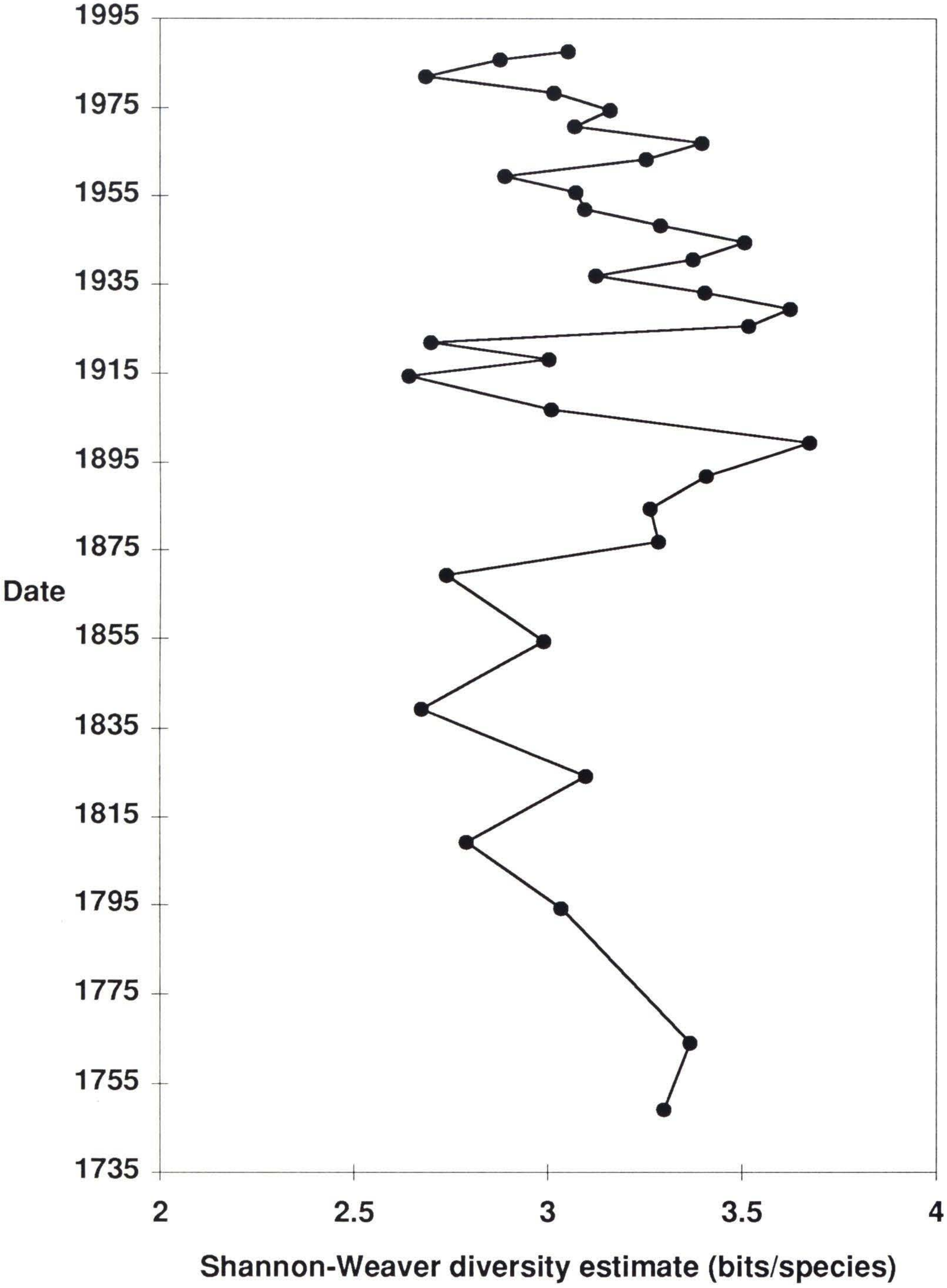


Figure 30. Shannon-Weaver estimate of diatom diversity (bits/species) over time in Sooke Reservoir.

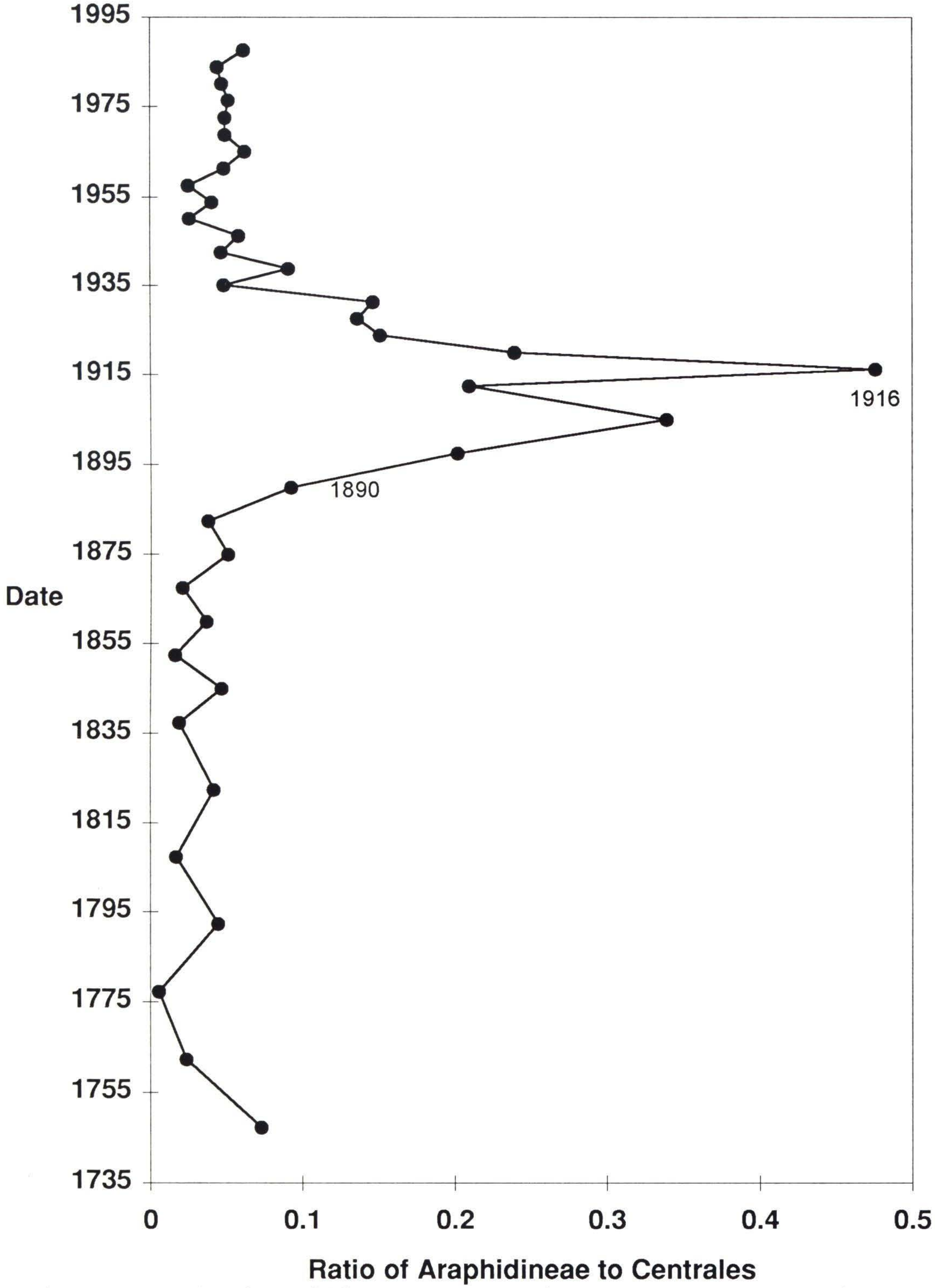


Figure 31. Ratio of araphidinate to centric diatoms over time in Sooke Reservoir.

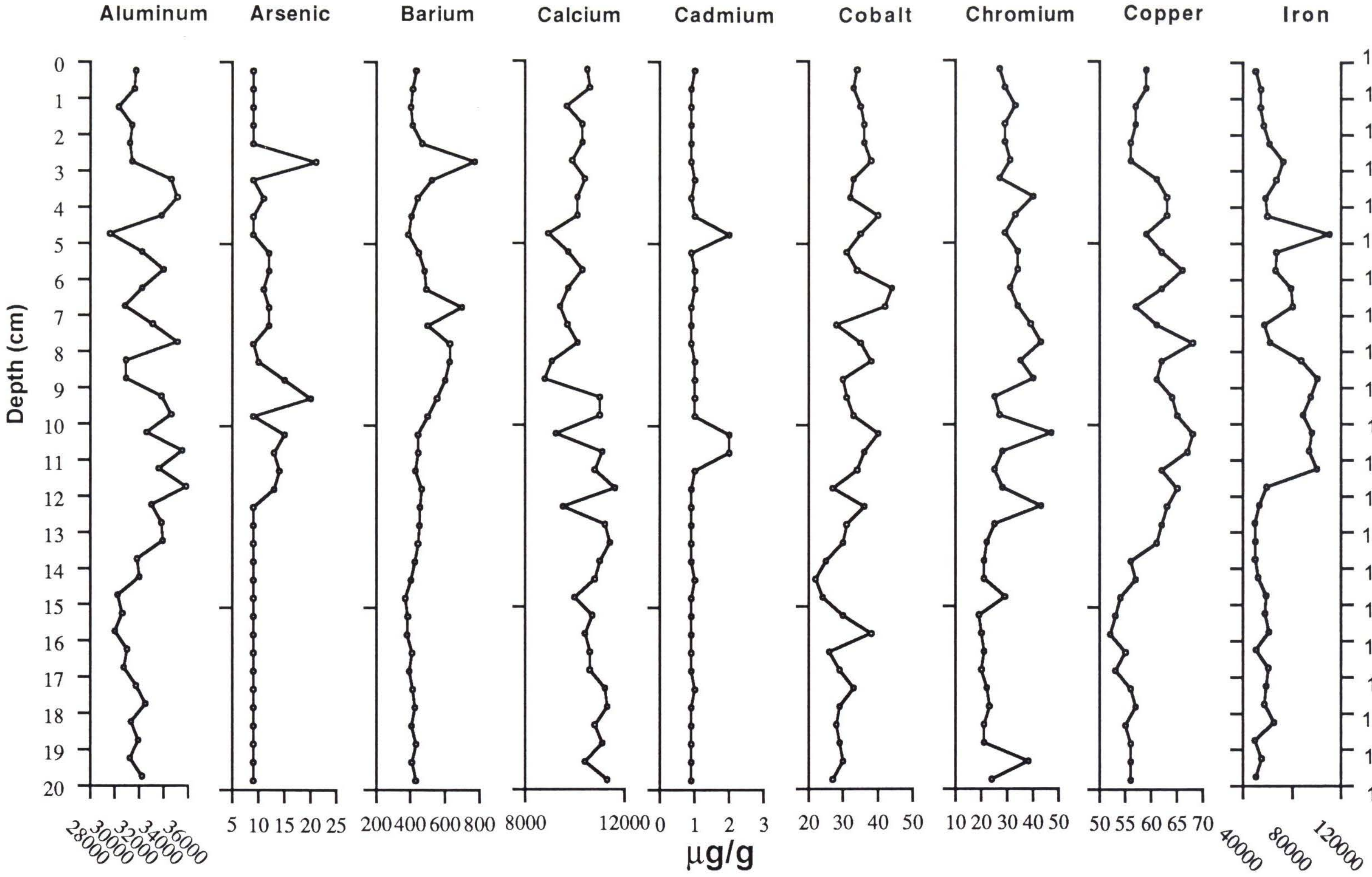


Figure 32. Metal concentrations (Al, Ar, Ba, Ca, Cd, Co, Cr, Cu, Fe) with depth per gram dry weight of sediment. Calculated dates are marked on the Y-axis at the right.

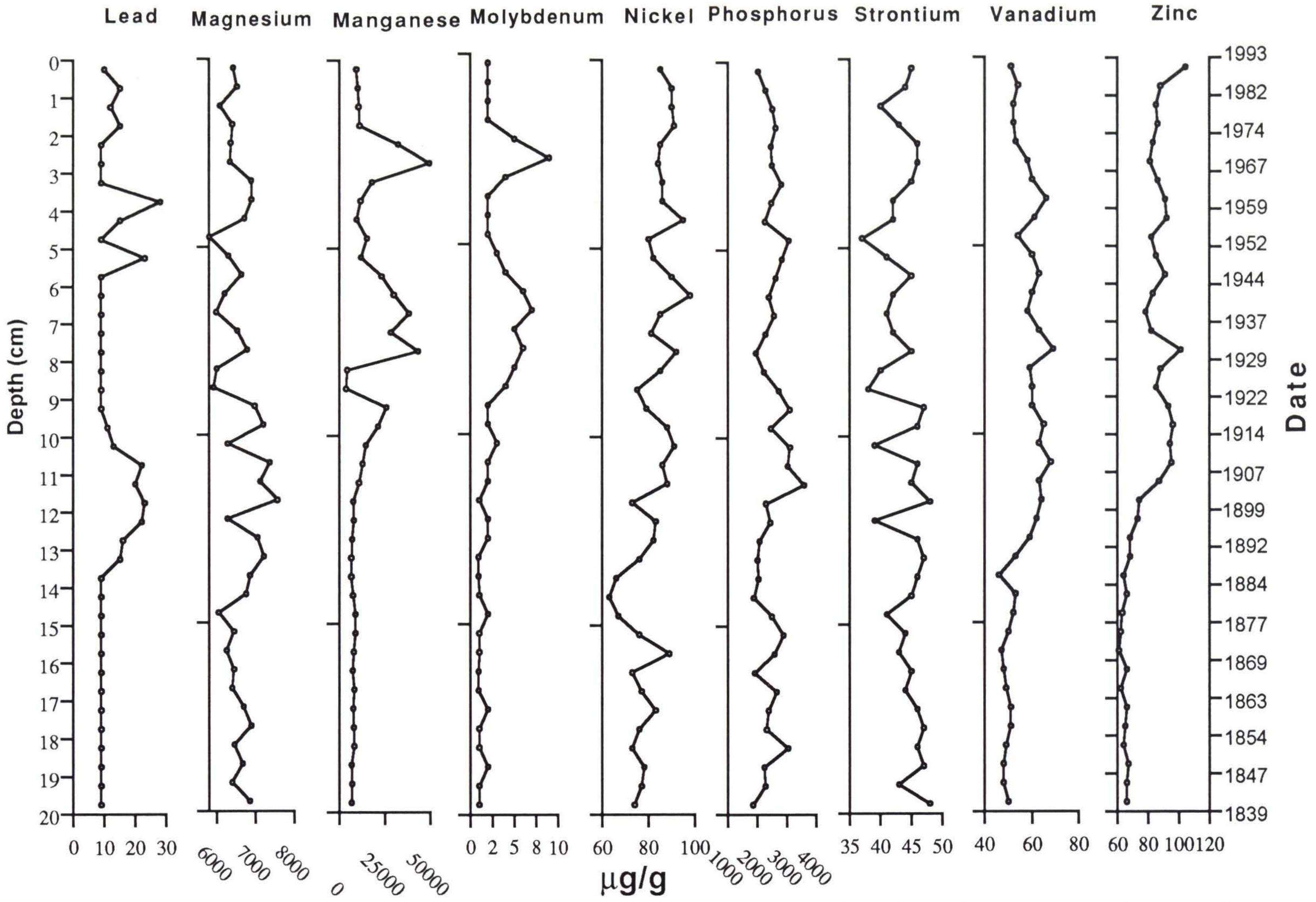


Figure 33. Metal concentrations (Pb, Mg, Mn, Mo, Ni, P, Sr, Va, Zn) with depth per gram dry weight of sediment. Calculated dates are marked on the Y-axis at the right.

Figure 34. Results of lead analysis performed on north basin core sectioned at 2 cm intervals. Concentrations before 1944 (6 cm) were not detectable.

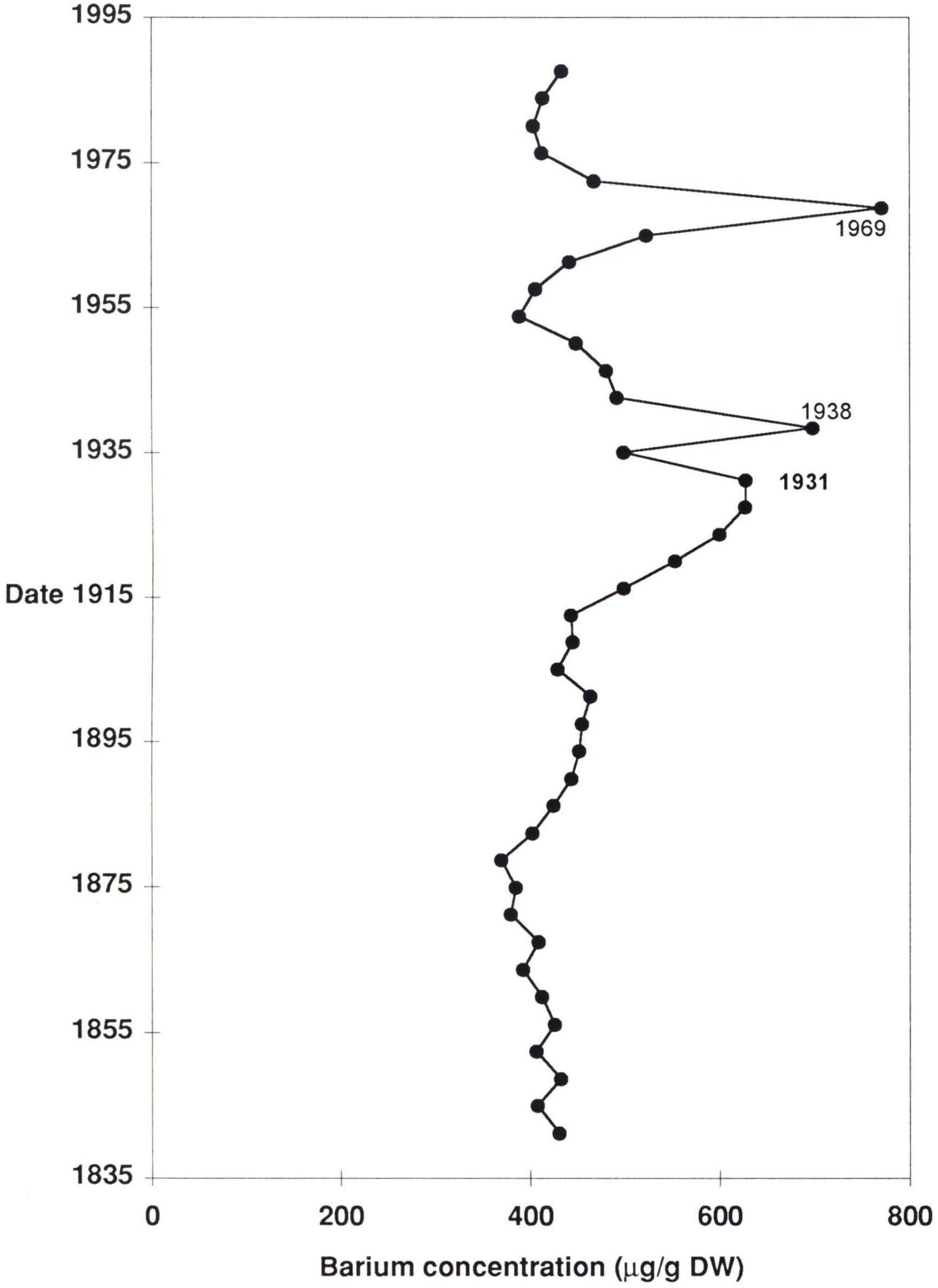


Figure 35. Downcore concentration of barium per gram dry weight of sediment for Sooke Reservoir.

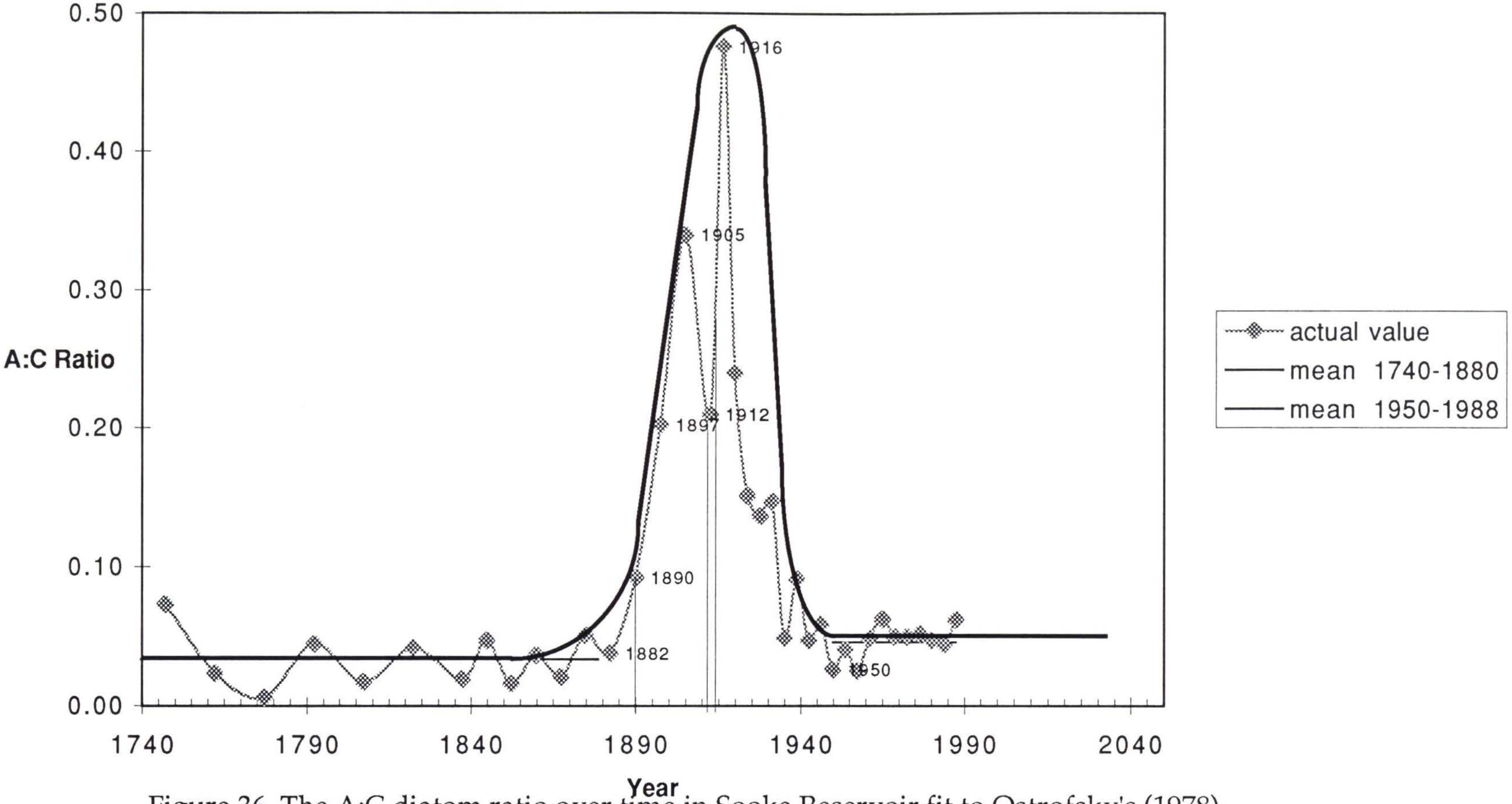


Figure 36. The A:C diatom ratio over time in Sooke Reservoir fit to Ostrofsky's (1978) model of predicted trophic upsurge.

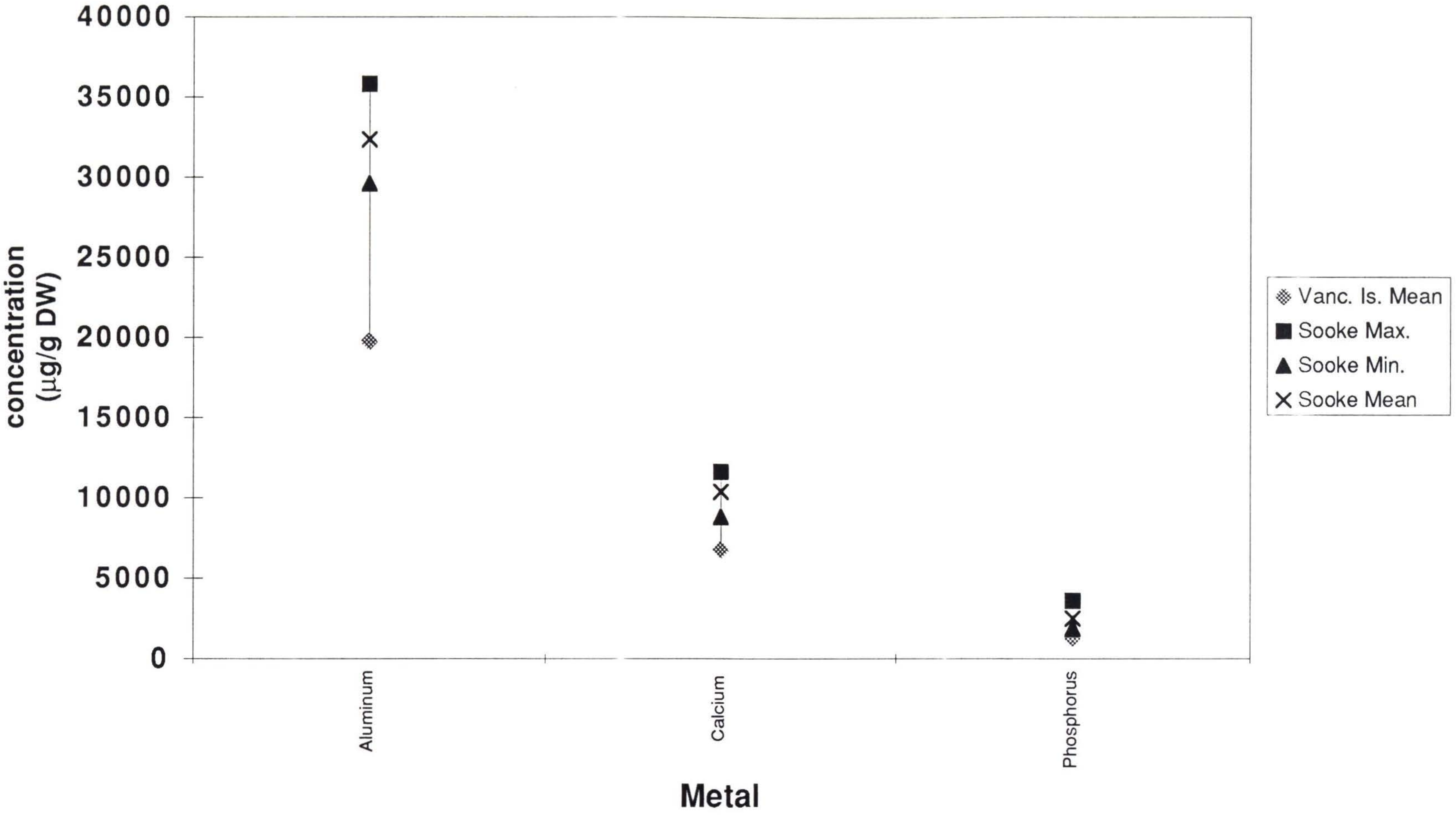


Figure 37. Sooke Reservoir metal concentrations (Al, Ca, P)per gram dry weight of sediment compared to the mean for 83 Vancouver Island lakes.

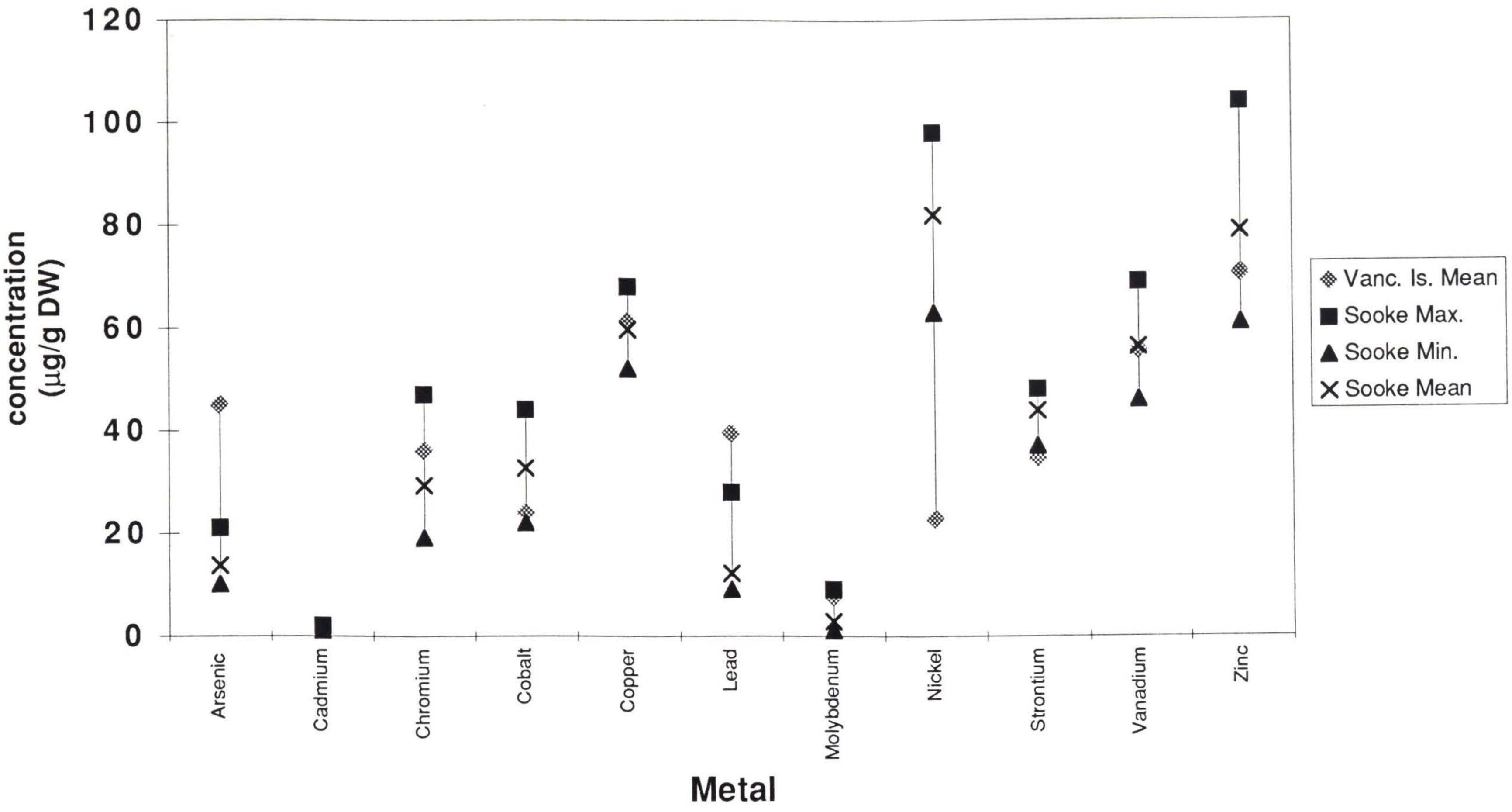


Figure 38. Sooke Reservoir metal concentrations (Ar, Cd, Cr, Co, Cu, Pb, Mo, Ni, Sr, Va, Zn) per gram dry weight of sediment compared to the mean for 83 Vancouver Island lakes.

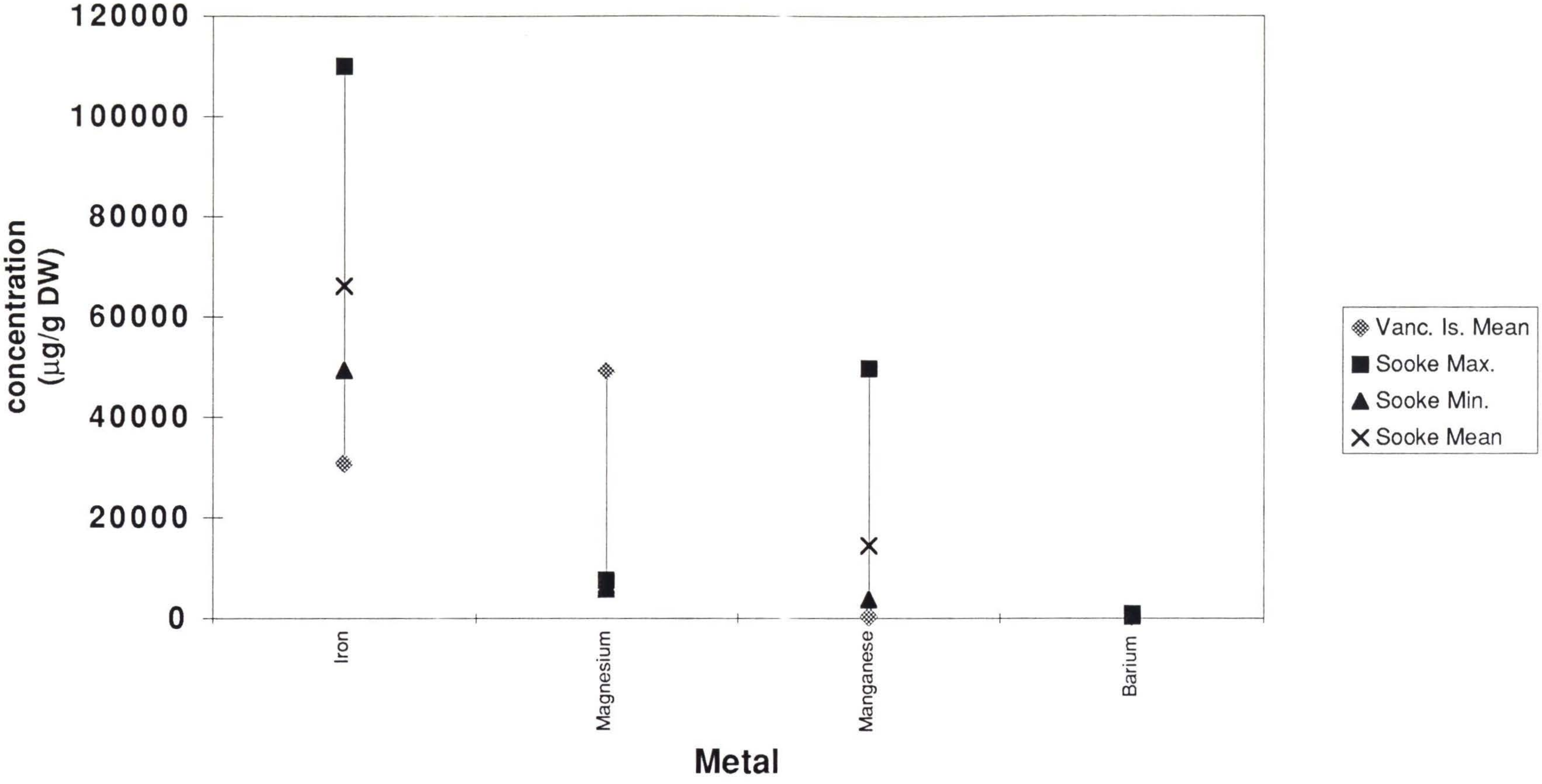


Figure 39. Sooke Reservoir metal concentrations (Fe, Mg, Mn, Ba) per gram dry weight of sediment compared to the mean for 83 Vancouver Island lakes.

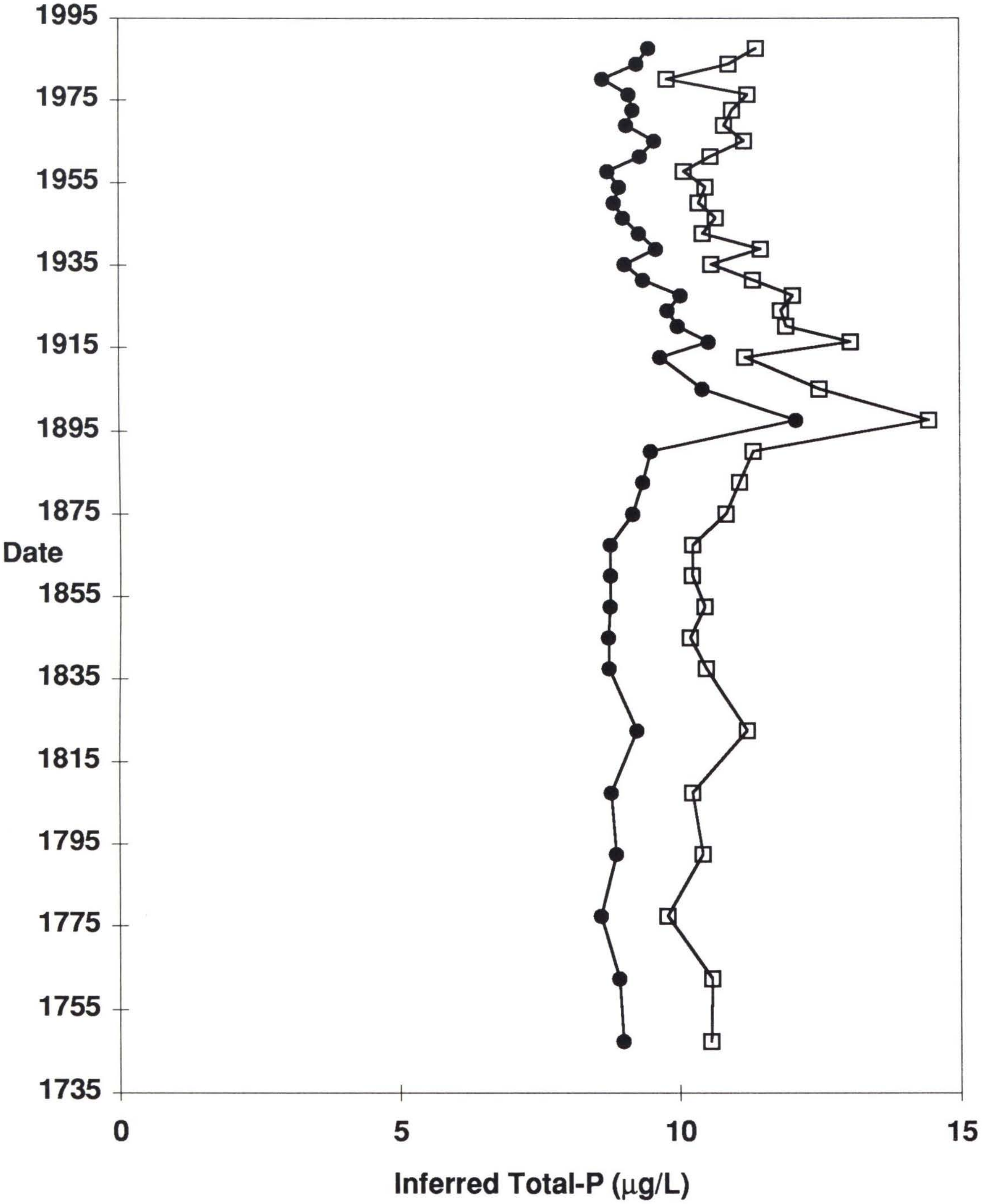


Figure 40. Total phosphorus concentrations over time in Sooke Reservoir inferred from weighted-averaging calibration using Cumming *et al.* 's (1995) calibration set (closed circles) and Reavie *et al.* 's (1995) calibration set (open squares).

Appendix A

Copies of historical data collected by the City of Victoria (date unknown), J. Thomas in 1949 and J.A. Balkwill in 1959 (Thomas, 1953; Balkwill, 1991).

The following are analyses of the Sooke and Goldstream waters. The City's water supply is obtained from these waters, the supply pipes being interconnected:

	Parts per Million City of Victoria	
	Sooke Lake Waterworks	Goldstream Waterworks
Sediment	0.9	0.3
Turbidity	None	None
Odour	None	None
Colour	Trace	Trace
Taste	None	None
Chemical Analysis		
Nitrogen as:		
Free Ammonia	0.01	0.01
Albuminoid Ammonia	0.03	0.02
Nitrates	0.68	0.42
Nitrites	None	None
Chlorine	0.4	0.3
Hardness	Negligible	Negligible
Alkalinity	None	None
Oxygen consumed	0.3	0.6
Solids:		
Volatile	16.0	10.5
Fixed	23.0	15.5
	39.00	26.00
Analysis of Fixed Solids		
Insoluable (SiO_2)	2.5	1.5
Ferric Oxide and Alumina	Trace	Trace
Lime (Ca)	10.0	7.0
Magnesia (MgO)	8.5	6.0
Chlorine (C_l)	0.4	0.3
Sulphate (SO_3)	Trace	Trace
Undetermined	1.6	0.7
	23.0	15.5

Temporary Hardness	0.9
Permanent Hardness	0.5
pH value	6.8

Microscopic Examination

Microscopical examination of these waters revealed extremely small amounts of fine silicious matter. In such insignificant amounts, this cannot be regarded as objectionable in the least.

Bacteriological analyses show the water to be free from pathogenic bacteria.

The temperatures for the water, taken from a tap in the City, were found as follows:

Month	Average Degrees F.
January	46.3
February	41.7
March	44.3
April	49.4

Month		Average Degrees F.
May	-----	57.4
June	-----	62.3
July	-----	66.2
August	-----	69.3
September	-----	64.0
October	-----	60.1
November	-----	51.3
December	-----	46.8

G. M. Irwin

G.M. Irwin,
City Engineer & Water Commissioner.

Improvement Districts

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS

MINES BRANCH
INDUSTRIAL MINERALS DIVISION

INDUSTRIAL WATER RESOURCES OF CANADA

Water Survey Report No. 5

Skeena River Drainage Basin, Vancouver Island, and Coastal Areas of British Columbia, 1949-51

By
J. F. J. Thomas

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1953

Price, 75 cents No. 839

TABLE III—*Continued*

Chemical Analyses of Civic Water Supplies—Continued

2. VANCOUVER ISLAND AREA, B.C.—Continued

(In parts per million)

Municipality	SHAWINIGAN LAKE	SIDNEY		SOOKE	VICTORIA	
Source(s)	Shawinigan Lake	Wells Nos. 1 and 2	Spring	Supplied by Greater Victoria Water Board	Sooke Lake	Goldstream Lake
	Raw and finished water	Raw and finished water			Raw and finished water	
Sampling point	**Direct from lake**	**Direct from pump**	**From pipe at spring**		City tap	City tap near Langford
Laboratory No.	**3518**	**3519**	**3381**		3359	**3392**
Field No.	498	499	500		477	478
Date of collection	Aug. 19/49	Aug. 20/49	Aug. 20/49		July 12/49	Aug. 12/49
Storage period (days)	73	72	17		12	25
Sampling temperature, °C.	19	11·0	10·5		20·0	19·0
Test temperature, °C.	20·3	20·5	21·7		23·9	21·1
Dissolved oxygen	......	......	......		......	......
Carbon dioxide (CO_2)	(2·5)	......	......		(2·0)	(3·5)
pH	7·1 (7·9)	7·5 (6·7)	6·8 (6·3)		7·4 (7·6)	6·9 (7·3)
Colour	10 (15)	3 (3)	0 (3)		5 (10)	10 (20)
Turbidity	0·8 (algae)	0·6	0·5		2	1
Suspended matter, dried at 105°C.	......	......	......	*See* Victoria, B.C.	......	......
Suspended matter, ignited at 550°C.	......	......	......		......	......
Residue on evaporation, dried at 105°C.	34·2	130	102		35·0	21·6
Ignition loss at 550°C.	13·8	37·6	21·4		13·8	8·4
Specific conductance (micromhos at 25°C.)	46·4	184	154		57·5	31·2
Calcium (Ca)	6·0	17·9	16·4		5·8	3·2
Magnesium (Mg)	1·0	5·4	4·0		1·7	0·6
Iron (Fe) Total	......	......	......		......	......
Dissolved	0·04	0·02	0·02		0·09	0·37
Sodium (Na)	2·0	10·0	6·4		1·6	2·0
Potassium (K)	0·1	0·9	0·4		0·3	0·3
Carbonate (CO_3)	0 (0)	0 (0)	0 (0)		0 (0)	0 (0)
Bicarbonate (HCO_3)	22·0 (24·4)	69·6 (70·8)	63·4 (66·4)		23·9 (24·4)	12·9 (13·4)
Sulphate (SO_4)	4·3	10·5	10·9		4·0	1·6
Chloride (Cl)	3·5	13·6 (13·6)	2·6		2·4 (2·9)	2·3
Fluoride (F)	0	0·05	0·05		0	0
Nitrate (NO_3)	Trace	14·2	0		0	Trace
Silica (SiO_2) Gravimetric	3·6	18	......		3·6	2·6
Colorimetric	4·4	18	20		4·6	2·8
Carbonate hardness, as $CaCO_3$, p.p.m.	18·0 (20·0)	57·0 (58·0)	51·8 (54·4)		19·6 (20·0)	10·5 (11·0)
Non-carbonate hardness, as $CaCO_3$, p.p.m.	1·1	24·8	5·6		1·9	0 (0·5)
Total carbonate hardness, as $CaCO_3$, p.p.m.	19·1	81·8	57·4		21·5	10·5 (11·5)
Saturation index	−2·4	−1·8	−0·97		−1·7	−3·0
Sum of constituents	32·1	125	91·9		32·1	19·4
Remarks:					Note high iron in No. 478 compared with No. 477. This may be due to iron pickup in system even though water ran 5 minutes prior to sampling.	

E: SOOKE

CALCULATIONS BY: DATE:

NO.	PLANIMETER READINGS 3.6731	AREA sq. in.	AREA Acres	Sum of An
5	83.50: 17488 15840 / 9140 7489 / 8348 8352 26.77: 8355 11042 / 5687 8355 / 2667 2687 101.82: 18030 18226 / 7862 8030 / 101.68 101.96 71.21: 10003 7122 / 2869 0013 / 7134 7109 6.92: 4772 5463 / 4080 4772 / 692 691	287.78	1057.04	1771
25	48.77: 10777 5650 / 5897 0777 / 4880 4873 .69: 4229 4300 / 4162 4229 / 67 71 .05: 4824 / 4819 / 05 1.36: 1262 1401 / 1130 1262 / 132 139 2.87: 5179 5462 / 4888 5179 / 291 283 .04: 6289 / 6280 / 9 85.82: 16789 15372 / 8207 6789 / 8582 8583 55.19: 12660 8177 / 7141 2660 / 5519 5517	194.51	714.45	
50	16.11: 7322 8931 / 5710 7322 / 1612 1609 5.39: 3641 4180 / 3101 3641 / 540 539 73.30: 12676 10002 / 5341 2676 / 7335 7326 43.44: 12487 6835 / 8128 2487 / 4359 4348	138.34	508.13	1222
75	7.95: 9780 10570 / 8980 9780 / 800 790 62.31: [illegible] 12385 / 4923 6161 / 6238 6224 31.74: 9931 13109 / 6763 9931 / 3169 3178 3.54: 2654 3008 / 2300 2654 / 354 354	105.54	387.66	895
100	1.58: 0725 0881 / 0564 0725 / 161 156 53.84: 7738 13858 / 2347 8481 / 5391 5377 18.71: 4933 6824 / 3061 4933 / 1872 1891 1363: 3161 3325 / 3000 3161 / 161 164	75.86	278.64	666.
125	.23: 0884 0905 / 0859 0884 / 25 21 40.34: 7828 11864 / 3796 7828 / 4032 4036 14.15: 8183 9603 / 6774 8183 / 1409 1420	54.72	200.99	479.
150	25.32: 4270 6785 / 1721 4270 / 2549 2515 10.06: 10555 1560 / 9541 0562 / 1014 998	35.38	129.95	336
SL.	.11: 3718 / 3707 / 11 .09: 3916 / 3907 / 9 .15: 5715 / 5700 / 15 .16: 5577 / 5561 / 16 .03: 6104 / 6101 / 3 .11: 6246 / 6235 / 11 1.56: 3443 4099 / 3287 3943 / 156 156 .17: 5953 / 5936 / 17 .03: 5848 / 5845 / 3 .03: 5822 / 5819 / 3	2.44	~~51.40~~	188.

* Note: The deepest contour area to be multiplied the mean depth in the area

Total

CALCULATIONS BY: DATE: PAGE: 12.5

PLANIMETER READINGS 3.6731	AREA sq. in.	AREA Acres	Sum of 2 acres An + Am	Volume acre h/2 (An+Am)
26.77 8355 11042 5688 8355 2667 2687 101.82 18030 18226 7862 8030 10168 10196 71.21 10003 7122 [illegible] 7134 7109 6.92 4772 5463 4080 4772 692 691	287.78	1057.04	1771.49	22143.
.69 4229 4300 4162 4229 67 71 .05 4824 4819 05 1.36 1262 1401 1130 1262 132 139 2.87 5179 5462 4888 5179 291 283 .09 6289 6280 9 85.82 [illegible] 15372 8207 6789 8582 8583 55.19 12660 8179 7141 2660 5519 5519	194.51	714.45		
5.39 3641 4180 3101 3641 540 539 73.30 12676 10002 5341 2676 7335 7326 43.44 12487 6835 8128 2487 4359 4348	138.34	508.13	1222.58	15282
62.31 6161 12385 9923 6161 6238 6224 31.74 9931 13109 6762 9931 3169 3178 3.54 2654 3008 2300 2654 354 354	105.54	387.66	895.79	11197
53.84 7737 13858 2347 8481 5391 5377 18.81 4933 6824 3061 4933 1872 1891 [illegible] 3161 3325 3000 3161 161 164	75.86	278.64	666.30	8328
40.34 [illegible] 11864 [illegible] 7828 [illegible] 4036 14.15 8183 9603 6774 8183 1409 1420	54.72	200.99	479.63	5995
10.05 10555 1560 9541 0562 1014 998	35.38	129.95	330.94	4136.
.15 5715 5700 15 .16 5577 5561 16 .03 6194 6191 3 .11 6246 6235 11 1.56 3943 4099 3787 3943 156 156 .17 5953 5936 17 .03 5848 5845 3 .03 5822 5819 3	2.44	[illegible]	188.35	2354

The deepest contour area to be multiplied the mean depth in the area

Total [illegible]

NAME: CALCULATIONS BY: D

AREA NO.	PLANIMETER READINGS	AREA sq. in.	AREA Acres
A 175	10.78 8229 9306 7149 8229 1080 1077 5.20 1997 2513 1473 1997 524 516	15.90	58.40
A 200	.22 1182 1203 1159 1182 23 21	.22	.81
A 25	.51 3864 3914 3811 3864 53 50 — .36 5873 5909 5834 5873 36 36 .48 6037 6083 5987 6037 50 46		
	Per 171.5" @ 400' = 68,300'		

Max 200

* Note: The deepest contour area to be multiplied the mean depth in the area)

Mean 65.4

CALCULATIONS BY: DATE: PAGE:

ETER READINGS				AREA sq. in.	AREA Acres	Sum of 2 acres An + Am	Volume h/2 (An
[illegible] 524	2513 1997 516			15.40	58.40	59.21	740
1203 1182 21				.22	.81		
						.81	.81
51 3914 3864 50		—	.36 5873 5909 5834 5873 36 36	.48 6037 6083 5987 6037 50 46			

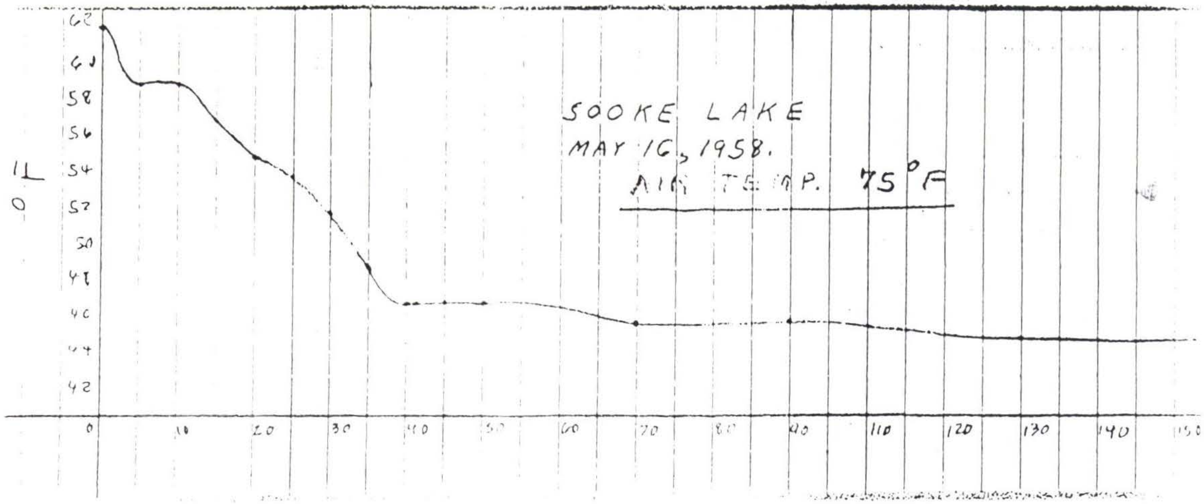
171.5" @ 400' = 68,600'

Max 200

The deepest contour area to be multiplied the mean depth in the area)

Mean 65.4

Total 70179


SOOKE LAKE
MAY 16, 1958.
AIR TEMP. 75°F
°F
62
60
58
56
54
52
50
48
46
44
42
0
10
20
30
40
50
60
70
80
90
110
120
130
140
150

VERTICAL TEMPERATURE RECORDSHEET FOR LAKES

Lake SOOKE Locality Victoria Station ....

Date May 15, 1959 Time .... Recorder ....

Cloud cover to O.C. Wind Velocity ....m.p.h. Direction ....

Air Temperature ...75° F................. Instrument Used ....

Remarks ....

....

Depth Surface	Temperature	Depth	Temperature	Depth	Temperature	Depth	Temperature
0	61°						
1		41		81			
2		42		82			
3		43		83			
4		44		84			
5	58°	45	46°	85			
6		46		86			
7		47		87			
8		48		88			
9		49		89			
10	58°	50	46°	90	45°		
11		51		91			
12		52		92			
13		53		93			
14		54		94			
15		55		95			
16		56		96			
17		57		97			
18		58		98			
19		59		99			
20	54°	60		100			
21		61		110			
22		62		120			
23		63		130	44°		
24		64		140			
25	53°	65		160			
26		66		180			
27		67		200			
28		68		225			
29		69		250			
30		70	45°	275			
31	51°	71		300			
32		72					
33		73					
34		74					
35	48°	75					
36		76					
37		77					
38		78					
39		79					

5	58	45	46°	85	
6		46		86	
7		47		87	
8		48		88	
9		49		89	
10	58°	50	46°	90	45°
11		51		91	
12		52		92	
13		53		93	
14		54		94	
15		55		95	
16		56		96	
17		57		97	
18		58		98	
19		59		99	
20	54°	60		100	
21		61		110	
22		62		120	
23		63		130	44°
24		64		140	
25	53°	65		160	
26		66		180	
27		67		200	
28		68		225	
29		69		250	
30		70	45°	275	
31	51°	71		300	
32		72			
33		73			
34		74			
35	48°	75			
36		76			
37		77			
38		78			
39		79			
40	46°	80			

.... 44°

LIGHT PENETRATION

....

....

....

OXYGEN

Series taken ....

....

....

DISSOLVED SOLIDS

Date	Total D.S.	Ca	Others

Reservoir Name: SOOKE LAKE Dam Name: SOOKE LAKE DAM

Drainage Information LOCAL
Drainage System: DRAIN → ____ → ____ → ____ → ____
Drainage area (above dam): ____ km²
Discharge (mean annual) at dam: ____ m³/s; at other outlets: ____ m³/s

Reservoir Morphometry
Reservoir location (centroid) __ ° __ N; ___ ° __ W
Elevation (max. pool) ____ m
Elevation (min. pool) ____ m
Drawdown (average) ____ m
Depth (max., max. pool) ____ m
Depth (mean, max. pool) ____ m
Shoreline development ____
Percent cleared ____
Surface area (max. pool) ____ km²
Surface area (min. pool) ____ km²
Volume (max. pool) .052 km³ (2)
Volume (min. pool) ____ km³
Dead storage ____ km³
Water exchange time ____
Shoreline length (incl. islands) ____ km

Dam Statistics
Location: __ ° __ N; ___ ° __ W
Dam Purpose(s) STORAGE
Dam height (max): 16 m
Length at top: 305 m
Ownership: GREATER VICTORIA WATER (2)
Date of first fill: 1967 (REBUILT)
Licenced 1915 (3)

Outlet Structures
Spillways - No. bays: ____
type: ____
Sluices - No. sluices: ____
Intake depth (below max. pool): ____
Turbines: Type(s) ____
Intake - depth below max. pool:
____ (No.) at ____ m
____ (No.) at ____ m
____ (No.) at ____ m
Screen type: ____

Fish Facilities (yes/no)
Fishway: ____; Hatchery: ____;
Spawning Channel: ____; Incubation Boxes: ____

Typical Water Quality Parameters			Date	Ref. No.
Spring P (total)		mg/L		
Spring N (total)		mg/L		
TDS		mg/L		
Chlorophyll a		ug/L		
Alkalinity (as $CaCO_3$)		mg/L		
pH				
Secchi (mid-summer)		m		

Typical freshet period: (day, mo.) ____ to (day, mo.) ____
Ice cover (number months per year) ____
Precipitation (mean annual): 46-152 cm/yr (4) Period: 19__ to 19__ at station ____
155-440 (4)

Watershed Information
Biogeoclimatic Zone Coast Doug Fir & C.West. Hemlock (4) Growing season 185-350 (4) days
Land ownership: % Crown ____; % private: ____; % municipal: ____; % Indian Reserve: ____
Basin land use: % forestry ____; % agriculture ____; % residential ____; % recreational ____;
% industrial ____; % miscellaneous ____
Recreational use: No. Parks ____; No. Campgrounds ____; No. Marinas ____; No. Boat Launches ____

Access: Town	km paved	km gravel	km dirt	km trail
VICTORIA				

Water Rights File No.: 281 722 (42,000 a-f) (3)

EQUIS Station Nos.: ____ ____ ____ ____ ____

Fish Species List (A = Abundant; M = Moderate; S = Scarce; P = Present, abundance unknown)

Species	Abundance	Ref. No.	Species	Abundance	Ref. No.

Comments

References (reports, papers, etc. where additional information can be found; see Bibliography)

Reference Number	Author(s) (year)	Main Subjects Addressed
1		Temperature/D.O. Data
2	REG OF DAMS IN CANADA	'70
3	Rick Nordin (pers. comm)	
4	Fowler	
5	U	✓
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		

watershed code 92-03-27
#930-0221-000

LAKE SURVEY DATA

SURVEYED BY: J.A.B.
DATE SURVEYED: May 15, 1959

NAME: Sooke Lake
MAP REF. CODE NO. 92B 12 K

DATA ON FILE:

Physical Data ____
Geography ____
Chemical ____
Flora ____
Invertebrates ____
Temperature Series ____
Obstructions & Pollutions ____
Stocking ____
General Information ____
Miscellaneous ____

Fish Samples ____
Stomach Analysis ____
Scale Reading ____
Resort & Campsite ____
Habitation ____
Access ____
Oxygen ____
Photography ____
Rehabilitation ____ Year ____

LOCATION:

Latitude, Longitude ~~48° 123°~~ N.W. 48° 33': 123° 42'

Drainage System - Sooke River - Sooke Basin - Juan De Fuca Strait

Elevation 568 feet

PHYSICAL DATA:

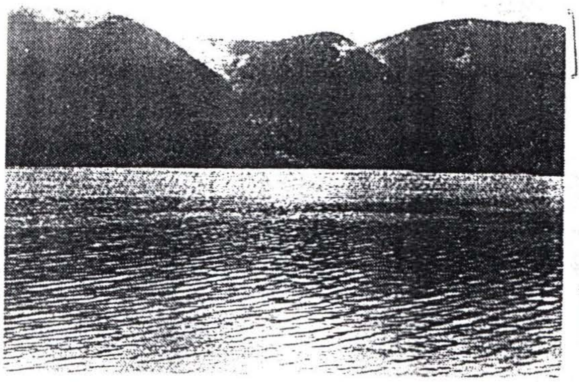
Surface Area	1057 acres	Volume	70,179 acre-feet
Shoreline Development		Shoreline Perimeter	68,600 feet
Maximum Depth	200 feet	Mean Depth	65.4 feet
Total Desolved Solids	53 p.p.m.	Secchi's Disc	

GEOGRAPHY:

Local Geography:

OCT 59

Lake Drainage:



SOOKE LAKE

GENERAL INFORMATION

ACCESS: Good. Public restricted at present by the Greater Victoria Water Board. Approximately 26 miles from Victoria.

RESORTS AND CAMPSITES: No resorts or other facilities.

OTHER HABITATIONS: Victoria water shed caretaker is the only inhabitant.

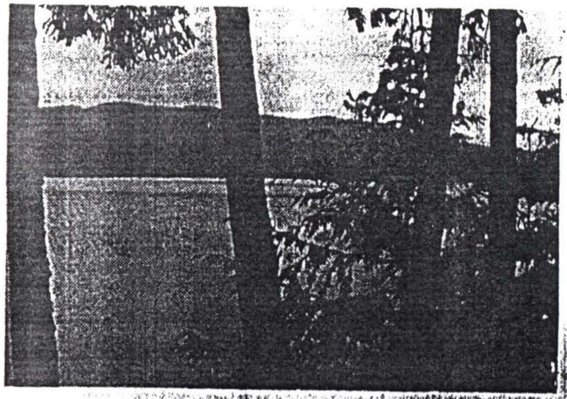
OBSTRUCTIONS AND POLLUTIONS: The Water Board dam is across the outlet and controls the creek flow.

GENERAL DESCRIPTION: Approximately 5 miles by 1 mile and is contained by mountains. Few shoal and marsh areas.

ocality ....SOOKE. LAKE..........Date ......May. 17,. 1958.......... Method of Capture ....Gillnetted...............

DATE	SPECIES	LENGTH	WEIGHT	SEX	COND.	AGE	STOMACH CONTENTS					
		~~cm.~~ in.	~~gm.~~ oz				Total Volume	Bottom Organisms	Plankton	Terr. Insects	Fish	REMARKS
ay 17/58												
1	Cutthroat	10½	8	F	Imm.							
2	"	10¾	6	M	"							
3	"	9½	6	M	"							
4	"	11½	10	M	"							
5	"	9½	5	F	"							
6	"	9½	5	F	"							
7	"	9¼	4	F	"							
8	DollyVarden	4¼	1		"							
9	"	7¼	3	F								
10	"	8¾	5	M								
11	"	7½"	3	M								
12	"	8½	4	M	"							
13	"	7¾	4	F	"							
14	"	8¼	4	F								
15	"	7¾	3	M								
16	Kokanee	8½	4	F	Imm.							

OCT · 59 ·



CHECKING LIST OF SPECIES

LAKE .....SOOKE.....................................

		SPECIMENS	SCALES	STOMACHS	RECORD ONLY
TROUT, CHAR					
Lake Trout	Savlelinus namaycush				
Dolly Varden	S. alpinus	X	X		
Brook Trout	S. fontinalis				
Brown Trout	Salmo trutta				
Cutthroat	S. clarki	X	X		
Steelhead	S. gairdneri				
WHITEFISH					
Round	Prosopium cylindraceum				
Mountain	P. williamsoni				
Pygmy	P. coulteri				
Lake	Coregonus clupeaformis				
Broad	C. nasus				
Least Cisco	C. sardinella				
Inconnu	Stenodus leucichthys nelma				
GRAYLING					
Arctic	Thymallus arcticus				
SUCKERS					
Coarse Scale	Catostomus macrocheilus				
White	C. commersonni				
Longnose	C. catostomus				
Bridgelip	C. columbianus				
Northern Mountain	Pantosteus jordani				
MINNOW					
Carp	Cyprinus carpio				
Goldfish	Carassius auratus				
Tench	Tinca tinca				
Redside Shiner	Richardsonius balteatus				
Squawfish	Ptychocheilus oregonense				
Northern Pearl Dace	Margariscus margarita nachtriebi				
Peamouth Chub	Mylocheilus caurinum				
Northern Redbelly Dace	Chrosomus eos				
Finescale Dace	Pfrille neogoea				
Chiselmouth	Acrocheilus alutaceum				
Flathead Chub	Platygobio gracilis				
Lake Chub	Couesius plumbeus				
Speckled	Rhinichthys osculus				
Leopard Dace	R. falcatus				
Longnose Dace	R. cataractoe				
Brassy Minnow	Hybognathus hankinsoni				
SCULPINS					
Prickly	Cottus asper	X			
Aleutian	C. aleuticus				
Spoonhead	C. ricei				
Torrent	C. rhotheus				
Slimy	C. cognatus				
Columbia	C. hubbsi				
BASS					
Smallmouth	Micropterus dolomieui				
Largemouth	M. salmoides				
Pumpkinseed	Lepomis gibbosus				
Black Crappie	Pomoxis nigromaculatus				

CHECK LIST OF SPECIES

LAKE ....

	SPECIMENS	SCALES	STOMACHS	RECORD ONLY
PERCH				
Yellow Perca flavescens				
Walleye Stizostedion vitreum				
TROUTPERCH				
Troutperch Percopsis omiscomaycus				
PIKE				
Northern Esox lucius				
CODFISH				
Burbot Lota lota				
CATFISH				
Brown Bullhead Ictalurus nebulosus				
Black Bullhead I. melas				
MOONEYES				
Goldeye Hiodon alosoides				
HERRING				
American Shad Alosa sapidissima				
SMELTS				
Eulachon Thaleichthys pacificus				
Longfin Spirinchus dilatus				
STICLEBACKS				
Three Spine Gasterostens aculeatus				
Brook Eucalia inconstans				
STURGEN				
White Acipenser transmontanus				
Green A. medirostris				
LAMPREYS				
Pacific Entosphenus tridentatus				
Western Brook Lampetra planeri				
Western L. ayresi				
SALMON				
Pink Oncorhynchus gorbuscha				
Coho O. kisutch				
Spring O. tshawytscha				
Chum O. keta				
Sockeye O. nerka				
Kokanee O. nerka kennerlyi	X	X		

FLORA AND INVERTEBRATE FAUNA

MACROFLORA

PLANKTON

Date, station	T.V. 10	T.V. 20	T.V. 3 ~~S.T. 10~~	S.T. 20
May 15, 1959	1.8 c.c.	1.9 c.c.	1.8 c.c.	

BOTTOM FAUNA

Date	Depth	Substrata	Organisms

Vita

Surname: Barraclough Given names: Cori Laurine

Place of Birth: Kimberley, British Columbia, Canada

Educational Institutions Attended:

University of Victoria	1987-1995
East Kootenay Community College	1986-1987
Selkirk High School	1982-1986

Degrees Awarded:

Bachelor of Education	University of Victoria	1992
Bachelor of Arts	University of Victoira	1990

Honours and Awards:

University of Victoria Graduate Teaching Fellowship	1994-1995
Nominated for the Dr. Maxwell A. Cameron Memorial Medal– British Columbia Teachers' Federation (University of Victoria, Secondary Education)	1991
B.C. Provincial Academic scholarship	1986
First class Cominco Academic scholarship	1986
United Steelworkers Local 651 scholarship	1986
United Steelworkers National Academic scholarship	1986

Publications:

Refereed Journals:

Lucey, Wm. P., B. Moore, B.T. Jeffs, **C.L. Barraclough**, K.E. Congdon, A.P. Austin. 1993. Impact of domestic waste waters from Whistler on the Cheakamus and Squamish Rivers. Canadian Water Resources Journal, Special Edition - Whistler and Water: building a city in the mountains. Conference Proceedings - May 6-7, 1993. pp. 49 - 70.

Lucey, Wm. P., B. Moore, B.T. Jeffs, **C.L. Barraclough**, K.E. Congdon and A.P. Austin. 1992. Impact on a pristine mountain river of domestic waste waters from remotely located, recreationally accelerated, development of a wilderness. Technical report. Canadian Journal of Fisheries and Aquatic Science. Technical Report No. 1879: 49-60.

Reports:

Barraclough, C.L. D.R. Grant, Wm. P. Lucey and A.P. Austin. 1994. Colwood Creek: Water Quality and Habitat Assessment: Summer 1994. Phase 8 Report. Prepared for the City of Colwood.

Grant, D.R., **C.L. Barraclough**, Wm. P. Lucey and A.P. Austin. 1994. Bilston Creek: Water Quality and Habitat Assessment Summer 1994, Final Report. Prepared for the District of Metchosin, Bilston Watershed Habitat Protection Association, Langford Electoral Area and Min. of Env., Lands and Parks.

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Barraclough. C.L. 1993. Sturgeon Bank (Iona Jetty) Fraser River Estuary sediment study Part II: Periphyton analysis: Diatoms. Prepared for Ministry of Environment Lands and Parks, Water Quality Branch, Water Management Division. 65 pp.

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Lucey, Wm. P., B. Moore, B.T. Jeffs, **C.L. Barraclough**, K.E. Congdon, A.P. Austin, 1993. Impact of domestic waste waters from a remotely located, recreationally accelerated, wilderness recreation facility on water and habitat quality in a pristine mountain river. **Proceedings of:** Whistler and Water: building a city in the mountains, Canadian Water Resources Conference. May 6-7, 1993.

Barraclough, C.L. K.E. Congdon, Wm. P. Lucey and A.P. Austin. 1992. Colwood Creek: Water Quality and Habitat Assessment. Phase 6 Report. Nov. 1992. prepared for the City of Colwood. 80 pp.

Congdon, K.E., **C.L. Barraclough**, Wm. P. Lucey and A.P. Austin. 1992. Bilston Creek: Water Quality and Habitat Assessment. Phase 2 report. Nov. 1992. Prepared for the Municipality of Metchosin, District of Langford and Ministry of Environment, Lands and Parks.

Lucey, Wm. P., B. Moore, **C.L. Barraclough**, B.T. Jeffs, K.E. Congdon and A.P. Austin. 1992. The proposed pipeline discharge of Whistler's treated sewage effluent to the Squamish River: a preliminary assessment. Summary Report, No. 92-01. University of Victoria, Department of Biology and B. C. Min. of Env., Lands and Parks, Environmental Protection Program, Lower Mainland Region. April 1992.

Austin, D.J.D., P.A. Cobban, Wm. P. Lucey, **C.L. Barraclough** and A.P. Austin. 1992. Colwood Creek: Water Quality and Habitat Assessment. Phase 5 report. April 1992. Prepared for the City of Colwood.

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Title of thesis:

Paleolimnological Elucidation of the Historical Water Quality of Sooke Reservoir, Victoria, British Columbia by Diatom Stratigraphic Analysis.

Author [redacted]
Cori Laurine Barraclough
September 29, 1995