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Limnological Effects of 19th Century Canal Construction and Other Disturbances on the Trophic State History of Upper Rideau Lake, Ontario

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ABSTRACT

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Upper Rideau Lake is a major lake in the Rideau Canal system; a waterway constructed in 1832 to link Kingston with Ottawa. The lake is currently borderline eutrophic, and local residents are concerned about its water quality. Long-term water chemistry data, however, are not available, and so we used diatom-based paleolimnological techniques to reconstruct the lake's development over the last two centuries. Our data indicate that Upper Rideau Lake was moderately productive even before European settlers began to affect this part of Ontario. The construction of the Rideau Canal, the first major anthropogenic disturbance in this system, greatly affected water quality. During the construction of the canal, the water level in Upper Rideau Lake was raised 1.5 m, resulting in increased nutrient and sediment loading, and an enlarged littoral zone. Deforestation associated with timber harvesting and agricultural activities maintained higher nutrient levels between ca. 1830 and the 1940s. Nutrient levels increased again over the last 40 years, with increased cultural activities in the drainage basin. Notwithstanding these more recent disturbances, the construction of the Rideau Canal in the early part of the 19th century had the largest impact on this lake.

Key Words: eutrophication, paleolimnology, diatoms, phosphorus, nitrogen, water level changes, canals.

The Rideau Canal is a series of lakes and rivers linked by locks and channels that connects Kingston and Ottawa, Ontario, Canada (Fig. 1). The canal was completed in 1832 in order to provide an alternate route connecting Lake Ontario with the Atlantic Ocean, primarily to transport military personnel and supplies to counter the threat of attack from the United States. After the St. Lawrence canal system was completed in 1851, the Rideau Canal's military purpose became obsolete. From 1850 until the 1930s, the Rideau Canal was used as a commercial waterway to transport timber, local produce, and people. After the Second World War, the canal was used primarily for recreation (Peck 1982).

Upper Rideau Lake serves as the headwater of the Rideau Canal, with one outlet flowing south to Lake Ontario via Newboro Lake, and the other outlet flowing north to the Ottawa River via Big Rideau Lake (Fig. 1). Upper Rideau Lake is presently boderline eutrophic, and its water quality is of considerable concern to local residents. However, as is the case with most lake systems, very little long-term limnological data are available for the lake, and so the cause of the lake's present condition is unknown. Fortunately, paleolimnological studies can provide proxy data for these missing monitoring data, and can therefore be used to document baseline (i.e., pre-impact) conditions, define natural variability, and identify the point(s) in time that the lake system began to change (Smol 1992).

Diatom-based paleolimnological studies have been used extensively to infer long-term changes in water quality (Dixit et al. 1992). Diatoms (class Bacillariophyceae) are a widely distributed algal group that possess taxonomically-specific silicified cell walls (frustules) that are often well preserved in lake sediments. Christie and Smol (1993) used Canonical Correspondence Analysis (CCA) to show that there was a good relationship between surficial diatom assemblages and measured environmental variables in alkaline lakes from southeastern Ontario. In their calibration study, the results of a series of constrained CCA's showed that total lakewater nitrogen (TN) concentration was the environmental variable that best explained the distribution of diatom assemblages from

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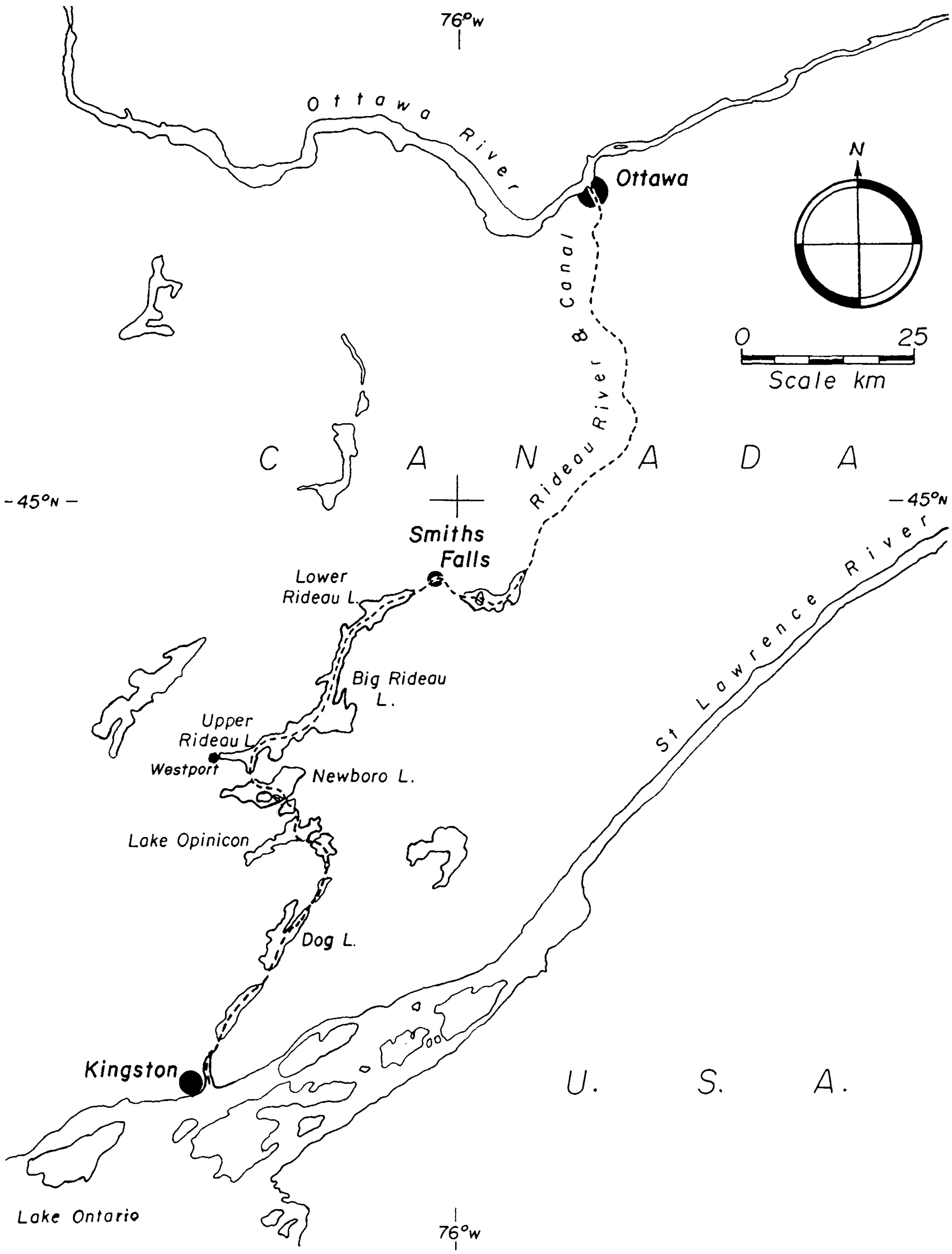

Figure 1.–Map of the Rideau Canal System showing the location of Upper Rideau Lake.

southeastern Ontario. Results of Monte Carlo permutation tests indicated that TN did not act independently of total phosphorus (TP), chlorophyll *a* or Secchi depth. Therefore, TN was selected to act as a proxy for these four closely-related variables to represent lake trophic status (for more details, see Christie and Smol 1993).

Weighted averaging regression and calibration (with classical deshrinking) were then used to develop a transfer function to reconstruct TN from the relative abundance of eighty-three diatom taxa from the surficial sediments of fifty-one lakes (Christie and Smol 1993). There was a good correlation between diatom-inferred TN concentrations and measured TN concentrations (r^2=0.75, n=51 lakes) (for further discussion, see Christie and Smol 1993).

In this study, we use the above transfer function to infer lake trophic status (represented by TN) from diatom assemblages preserved in the sediments from Upper Rideau Lake. These data will be used in conjunction with historical land-use data and ^{210}Pb dating to quantify the sequence and extent of nutrient enrichment related to human activity in the watershed area of Upper Rideau Lake.

Site Description

Upper Rideau Lake (44° 41' N, 76° 20' W, elevation 124 m asl) is a large (surface area = 13.62 km^2), alkaline (pH = 8.3, alakalinity = 99 mg $CaCO_3 \cdot L^{-1}$) lake with a maximum depth of 22 m and a mean depth of 8.05 m. Fifty-three percent of the lake is presently littoral zone (unpubl. data, Ontario Ministry of the Environment). Most of the shoreline is Cambrian conglomerate sandstone, shale and dolostone (Ministry of Northern Development and Mines 1991). The lake drains a watershed of 155 km^2. The north shore is a steep forested hill, while the southern portion is agricultural land. In 1983, 291 cottages and permanent residences surrounded the lake. The lake has one inlet, draining a series of three lakes (Clear, Wolfe, and Westport Sand), and has two outlets, one draining north into Big Rideau Lake and the other draining south into Newboro Lake (Fig. 1).

Upper Rideau Lake is currently borderline eutrophic. For example, measurements conducted by the Ontario Ministry of Environment for 1971, 1975, 1983, noted mean total phosphorus (TP) concentrations of 31, 26, and 38 µg · L^{-1}, and total nitrogen (TN) of 585, 523, and 559 µg·L^{-1}, respectively.

Materials and Methods

A sediment core was retrieved from the lake using a Glew (1989) gravity corer, a sampler specifically designed to allow for high-resolution work on recent

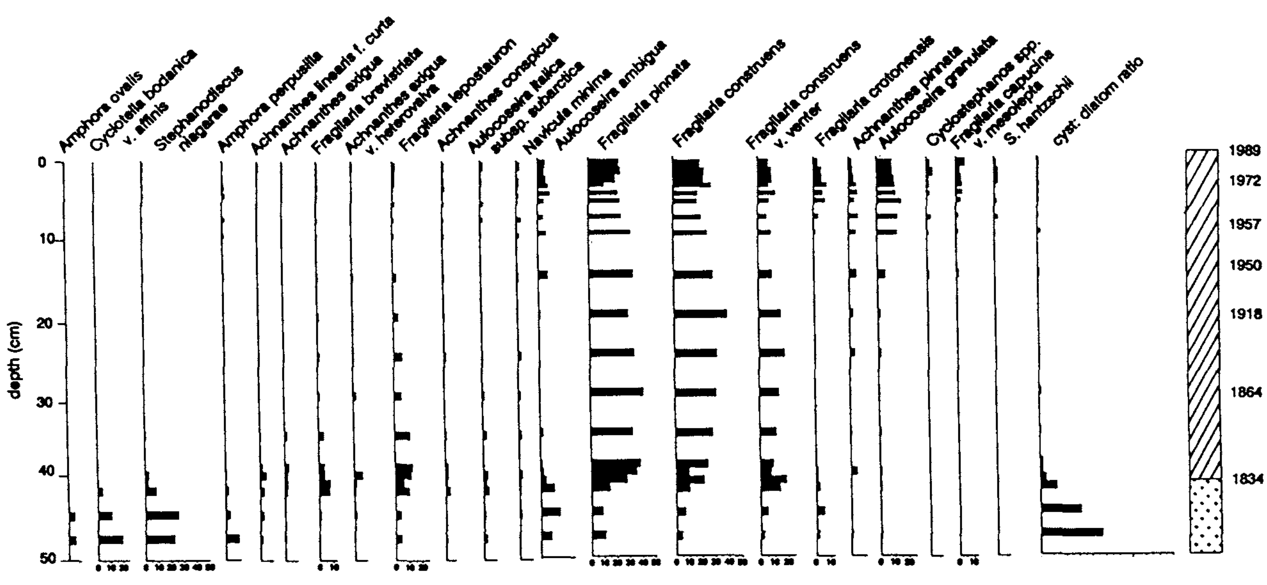

Figure 2.–Summary relative frequency diagram of the most common diatom species recorded in the Upper Rideau Lake sediments. ^{210}Pb dates are shown to the right. The construction of the Rideau Canal was also delineated in the sediment record by a shift from light brown sediments (stippled) to a dark brown organic gyttja (diagonal lines) as shown to the right of the diagram. The cyst:diatom ratio is a relative measure, expressed as a percentage, following Smol (1985).

lake histories (Cumming et al. 1993). The core, which was taken from a depth of 6.5 m in a flat section of the lake bottom, was extruded using a modified upright piston extruder (Glew 1988) into 0.25 cm intervals from 0 to 3 cm core depth, 0.5 cm intervals from 3 to 10 cm, and the remainder of the core at 1 cm intervals. Samples were stored in polyethelene Whirl-Pak bags and refrigerated.

Diatom slides were prepared and enumerated the following procedures outlined in Smol (1983). Diatom valves were identified along transects using a Nikon microscope with Nomarski optics at 1000x magnification. For the top 3 cm, a minimum of 125 valves were identified for each 0.25 cm interval and combined to yield the results shown in Fig. 2. For the remainder of the core, a minimum of 500 diatom valves were recorded and identified to the species level or lower, primarily using the taxonomic sources listed in Christie and Smol (1993). Chrysophyte cysts were also enumerated and expressed relative to the number of diatom valves enumerated (Smol 1985).

The program, WACALIB v. 2.1 (Line and Birks 1990), was used to infer changes in TN concentration in the core profile based on weighted averages of the diatom assemblages from a calibration set of lakes from southeastern Ontario (Christie and Smol 1993).

The cores were dated by ^{210}Pb chronology, using the constant rate of supply (CRS) model (Oldfield and Appleby 1984), in Binford's (1990) computer program, in order to develop the depth-time profile.

Results and Discussion

Three zones can be identified visually based on the ^{210}Pb dates (Fig. 2), changes in the diatom stratigraphy (Fig. 2), and the diatom-inferred limnetic TN concentrations (Fig. 3). Zone 3 (48 cm to 42 cm) represents the period before 1832. Zone 2 begins at the 42 cm level (ca. 1832), when the Rideau Canal was constructed. The boundary between these two zones was delineated by a striking lithological change in the sediments (Fig. 2) that was accompanied by changes in the diatom assemblages (Fig. 2) and increased values for diatom-inferred TN (Fig. 3). Zone 1 (10 cm to the surface) represents the period of recent cultural disturbances in the lake from ca. 1955 until 1990.

Zone 3 (Pre-disturbance era)

According to the ^{210}Pb dates, the section of the core below 42 cm (Zone 3) represents lake conditions prior to the construction of the Rideau Canal (Fig. 2). The diatom assemblage was dominated by *Cyclotella bodanica* v. *affinis*, *Stephanodiscus niagarae*, *Amphora ovalis* and *A. perpusilla* (Fig. 2). These taxa are generally characteristic of relatively unproductive to moderately productive waters (Christie 1993). The diatom-inferred TN concentrations were relatively low (368-502 $\mu g \cdot L^{-1}$) (Fig. 3). In southeastern Ontario, lakes with TN concentrations below 500 $\mu g \cdot L^{-1}$ generally have chlorophyll *a* concentrations below 4 $\mu g \cdot L^{-1}$ (Christie and Smol 1993), and are classified as mesotrophic.

The cyst:diatom ratio was relatively high in Zone 3 (Fig. 2), indicating an abundance of chrysophytes (Smol 1985). With few exceptions, chrysophytes are rarely abundant in eutrophic waters in southern Ontario (Nicholls 1976) and so the ratio further indicates that compared to the lake's more recent history, the lake was comparatively less productive prior to the construction of the Rideau Canal.

Written records report that there was modest cultural disturbance in the watershed prior to the construction of the Rideau Canal. By 1819, there were four families of settlers in the area. One sawmill was built at Westport in 1817, and another was built in 1827 (McKenzie 1967). It is unclear when the forests beside Upper Rideau Lake were cleared; however, if some deforestation did occur at this time, it may have resulted in some erosion and nutrient loading into Upper Rideau Lake (Fig. 3). This may account for the increasing trend in inferred TN during this period (Fig. 3), which is driven by species changes such as a modest decline in oligotrophic taxa such as *Cyclotella bodanica* v. *affinis* (Fig. 2).

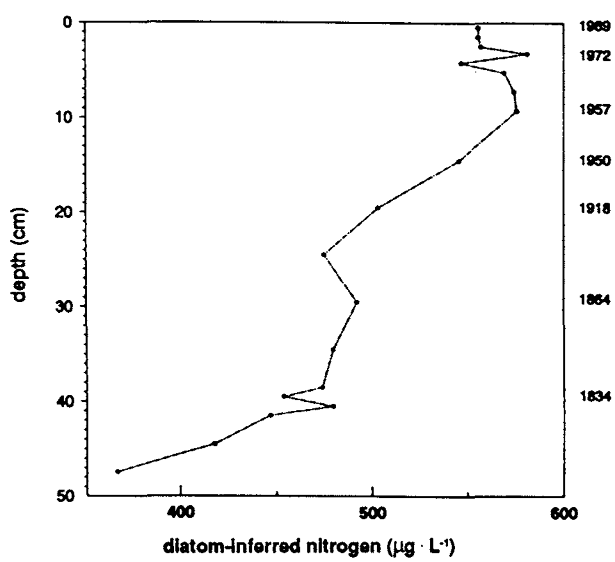

Figure 3.–Trends in diatom-inferred total nitrogen (TN) concentration for Upper Rideau Lake, using the transfer function developed in Christie and Smol (1993). The ^{210}Pb-inferred dates are shown to the right.

Zone 2 (Canal construction and land clearance era)

The marked change from light brown sediments to a dark brown gyttja at the 42 cm level mark the boundary to Zone 2 (Fig. 2). According to the ^{210}Pb dates, the sediments from the 39-40 cm interval were deposited ca.1834 (Fig. 2). At this time, the diatom flora changed to an assemblage dominated by small *Fragilaria* spp. (especially *F. pinnata, F. construens, F. construens v. venter*), while the cyst:diatom ratio approached zero (Fig. 2). The diatom-inferred values for TN fluctuate between 504 and 557 $\mu g \cdot L^{-1}$ (Fig. 3).

Work on the Rideau Canal began in the summer of 1827 at both ends of the canal (Kingston and Ottawa) and at the isthmus between Upper Rideau Lake and Newboro Lake (formerly Mud Lake) (Legget 1986). Early plans for the canal showed that the builders anticipated cutting through the isthmus and maintaining a 53 km (33 mile) long summit reservoir stretching from the outlet of Big Rideau Lake to the locks at Chaffeys Mills (at the inflow to Lake Opinicon, formerly Mosquito Lake) (Fig. 1). It proved to be extremely difficult to cut through the isthmus because of the bedrock. Alternately, a lock was constructed at the junction between Big Rideau Lake and Upper Rideau Lake to raise the water level by almost 1.5 m. This action saved the builders the problem of excavating a corresponding depth of rock on the isthmus cut between Upper Rideau and Newboro lakes (Legget 1986, Passfield 1982).

Raising the water level in Upper Rideau Lake by 1.5 m (sometime between 1829 and 1831) had several effects on the water quality. This flooding likely resulted in increased sedimentation and nutrient loading which was reflected by increased diatom-inferred values for TN (Fig. 3) and the near disappearance of chrysophytes (Fig. 2). The striking changes noted in the physical appearance of the core at 42 cm, with sediments changing from a light brown colour to a darker brown gyttja (Fig. 2), also distinguish this period.

Secondly, the flooding likely resulted in increased turbidity and decreased light availability resulting from the resuspension of particles. Barker (1834) describes one of the stories that emigrants were told to deter them from passing to Kingston via the Rideau Canal:

> ". . . on entering Mud Lake [now Newboro Lake] a large scoop or shovel is placed in the hands of each passenger, who will be compelled to enter the water and make a way through the soft mud for the steamboat to pass, the passage filling up as the vessel passes." (p. 28)

The flooding event also created a larger littoral zone in which the periphytic *Fragilaria* and *Achnanthes* taxa could thrive. Information about the trophic status of these *Fragilaria* taxa is controversial, as they are reported from a wide range of environmental conditions in shallow lakes from a number of sites (Christie 1993). It is likely that their presence in Upper Rideau Lake in Zone 2, as well as increases in epiphytic *Achnanthes* taxa, indicated that the littoral zone was expanded following the flooding from 1828 to 1831.

Before the Rideau Canal was built, an extensive forest of pine and hemlock covered the northern shores, while a maple-beech forest covered the southern shores (Ontario Ministry of Culture and Recreation 1981). Following canal construction, deforestation for timber products and agricultural activity maintained the elevated levels of nutrients in Zone 2. Furthermore, deforestation accelerates spring-melt of snow, resulting in increased rates of run-off and increased nutrient and sediment loads to receiving waters.

The Canal opened up the region for exploitation. In 1832, a half a million cubic feet of timber were cut and rafted out along the Rideau waterway (Ontario Ministry of Culture and Recreation 1981). A watercolor picture by Thomas Burrowes, entitled 'Upper Rideau Lake: Canoe en route to Bytown; Westport in the distance', painted some time after 1832, shows barren hills surrounding Westport (Passfield 1982). By the mid-1800s, square lumber was still being floated to Ottawa and Montreal. In 1850, two million feet of lumber were shipped from Westport alone (McKenzie 1973). Sawn logs were also cut as early as 1836 and taken to Kingston via the Rideau Canal where they were loaded on schooners and shipped to the United States (Ontario Ministry of Culture and Recreation 1981). By 1873, the hillside north of Westport was denuded of trees (McKenzie 1967) and other sketches of buildings in the village of Westport ca. 1873 (specifically the Woolen Factory of Joel Clark, and the residence and mill of W.H. Fredenburgh) show severely deforested areas in the background (McKenzie 1973).

Clearings created during the removal of timber products were often maintained for agricultural purposes. Barker (1834) described the land surrounding Upper Rideau Lake as "...a tract of country highly worthy of the attention of the emigrant for the land is generally good". In 1832, only 1,050 acres had been cleared in the Westport area, however, by 1873, 14,553 acres had been cleared (McKenzie 1973). Increased soil erosion and nutrient loading would have occurred with agricultural activity in the catchment basin.

Zone 1 (Modern era)

Zone 1 was characterized by increased diatom-inferred TN (557-586 $\mu g \cdot L^{-1}$) (Fig. 3) that may be related to the use of fertilizers, effluent inputs, and increased recreational use of the Rideau Canal (e.g., cottages and boating) following the Second World War (Legget 1986).

While the diatom taxa continued to be dominated by *Fragilaria pinnata* and *F. construens* as in Zone 2, the relative percentage of other taxa characteristic of more productive conditions (e.g. *F. crotonensis, F. capucina* v. *mesolepta, Aulacoseira granulata, Cyclostephanos* spp., and *Stephanodiscus hantzschii*) increased in this zone (Fig. 2). *A. granulata* is a summer-blooming taxon that is commonly found in nutrient-enriched sites in southeastern Ontario and other locations (Brugam 1983, Ennis et al. 1983, Stoermer et al. 1981). *F. crotonensis* is a eutrophic species found in a variety of lake conditions (Stoermer et al. 1985), and is often considered a reliable indicator of cultural disturbance associated with increased nutrient loading (Brugam and Patterson 1983, Ennis et al. 1983, Engstrom et al. 1985, Brugam 1988).

After ca.1972, *Fragilaria capucina* v. *mesolepta* increased slightly in relative abundance. This taxon is also commonly found in productive systems (Shuette and Bailey 1980). Although it was not very abundant in the calibration set from southeastern Ontario (Christie and Smol 1993), it was most abundant (9%) in a relatively productive lake (TN = 580 $\mu g \cdot L^{-1}$) (Christie 1993). Other taxa commonly found at nutrient-enriched sites, such as *Stephanodiscus hantzschii* (Brugam 1983, Brugam and Patterson 1983, Anderson 1989) and *Cyclostephanos* spp. (Anderson 1989), increased in the post-1972 sediments, perhaps in response to the nutrient loading from a sewage lagoon that was constructed in 1972 to service the village of Westport (Fig. 1).

Conclusions

Our paleolimnological data clearly show the link between significant increased human activity and deterioration of water quality. Using our diatom transfer function, in conjunction with autecological data for the dominant diatom taxa, ^{210}Pb dating, and historical land-use data, we can infer that Upper Rideau Lake was a moderately productive lake prior to the construction of the Rideau Canal (ca.1832). During construction of the canal, the water level in Upper Rideau Lake was raised by 1.5 m, resulting in increased nutrient loading to the lake and the development of an increased littoral zone. The construction of the Rideau Canal was the most significant event affecting Upper Rideau Lake during the last two centuries.

Deforestation (associated with timber removal and agriculture) elevated nutrient levels further in the lake between 1832 and the 1940s. Nutrient levels again increased in the latter part of this century, likely as a result of increased recreational use of the lake, use of fertilizers, and sewage. The increased relative abundance of taxa common at nutrient-enriched sites (e.g., *Stephanodiscus hantzschii* and *Cyclostephanos* spp.) at the top of the core may indicate that the water quality in Upper Rideau Lake is still deteriorating. Nonetheless, the lake's development was changed most dramatically by the construction of the Rideau Canal, almost two centuries ago.

Finally, this study confirms the conclusions of a growing volume of literature which demonstrates that paleolimnological perspectives can provide important information that cannot be attained using other methods (Smol 1992). Such paleolimnological data can be used by lake managers and policy makers to make more effective decisions on lake management and restoration strategies.

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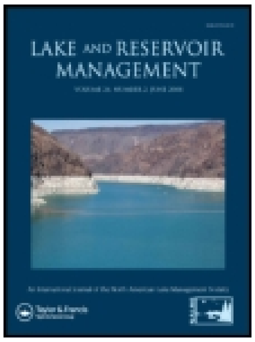

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