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2-3. Generic Approaches Towards Water Quality Monitoring Based on Paleolimnology

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Abstract

Long term environmental records for lake and river ecosystems provide a valuable generic tool for water quality management. These data sets can play a pivotal role in determining natural baseline conditions, detecting early evidence of change, identifying the causal mechanisms of water quality deterioration, and in gauging the success of remediation measures. At most sites, however, such data are sparse or completely lacking. New advances in paleolimnology, that is the study of past environments based on the analysis of sediments, offer considerable potential for reconstructing these historical records. This paleolimnological approach is illustrated by way of water quality research on three ecosystems in Québec, Canada. Lake St-Augustin is a small lake characterized by episodes of bottom-water anoxia and summer blooms of cyanobacteria that result in its municipal closure to swimming and other lake activities for several weeks each summer. A paleolimnological analysis based on fossil diatoms showed that there have been four phases of nutrient enrichment over the last 240 years coinciding with initial colonisation and land development (1760-1900), farm development (1900-1950), increased fertiliser use and intensification of agriculture (1950-1980), and major road and residential expansion (1980-present). The paleolimnological application of diatom-based transfer functions for total phosphorus analysis of Lake St-Charles, the principal drinking water supply for Québec City,

showed that substantial changes took place in the lake coincident with the raising of water level in the 1930s. There was no evidence of increasing eutrophication since that time, contrary to public perception. Finally, geochemical analysis of sediments in the St-Lawrence River showed greatly reduced concentrations of heavy metals and other pollutants over the period 1960-90, but the paleolimnological record also underscores the need for ongoing improvements in pollution control measures.

Introduction

The restoration and protection of freshwater ecosystems is an increasingly important priority for many environmental and conservation agencies throughout the world. A common problem in water quality management is the absence of reliable long term data series that provide information about the natural (pre-anthropogenic) "baseline" conditions in lakes and rivers that can be used to gauge the importance of measured or perceived changes in the present-day environment. For some freshwater issues it is important to detect early evidence of change and to know for how long that trend has persisted. This in turn raises questions such as whether any changes in key water quality variables are accelerating, whether these values have moved outside the bounds that were typical of the lake or river in the past, and whether there are natural cycles of variability to consider. For some issues it may be important to date precisely any past shifts in water quality and thereby identify causal changes in the surrounding catchments. Finally, for those lakes and rivers undergoing costly rehabilitation, it is important to determine how fast the waters are recovering, and to what extent the environment is returning to conditions prior to industrial, urban or rural development. Such information will help to guide ongoing treatment decisions and to set realistic legal or management goals (Rast and Holland 1988), as well as give important feedback to stakeholders including regulatory and funding agencies, politicians and the public. All of these questions require detailed long-term records, but in most cases such data are sparse or completely lacking.

Over the last two decades, paleolimnology, that is the study of past environments based on the analysis of lake sediments, has come to prominence with a suite of new high resolution sampling and dating protocols, new analytical approaches and refined statistical techniques for model building and application. Paleolimnological approaches have achieved success in helping to understand how lakes and their associated drainage basins respond to many types of environmental change including acidification, drought, temperature and other climatic shifts, nutrient enrichment and pollution by

contaminants (reviewed in Smol 2002). Of special interest to the management of lake water quality, these techniques now allow a detailed, high-resolution record of environmental variables to be reconstructed on the basis of sediment cores obtained from lakes, ponds, reservoirs, wetlands, peatlands and large rivers. Paleolimnological analysis provides a compelling example of how a generic (global) approach can be applied to specific sites, although regional and local knowledge is still necessary for reliable interpretations.

In this chapter we describe the basic steps in paleolimnological analysis and then examine three case studies in the province of Québec, Canada, illustrating the types and utility of this approach. We first examine Lake St-Augustin where the appearance of cyanobacterial blooms has resulted in restrictions on the use of this lake for recreational purposes. Our second example is Lake St-Charles, drinking water supply for the city of Québec, where perceived changes in water quality as well as recent limnological measurements from the lake have created public concern. Our third example is the St-Lawrence River where an expensive program to identify and control industrial pollution has raised questions about the degree of recovery and the efficacy of ongoing control measures. Finally we conclude by summarizing some of the strengths, limitations and additional requirements of the paleolimnological approach to water quality monitoring and management.

Paleolimnological Analysis

The key steps in paleolimnological analysis are sediment coring, splitting and dating; geochemical and paleobiological analysis of the subsamples; and the development and application of transfer functions to reconstruct past environmental conditions (Fig. 1).

Sediment sampling and dating

Sediment coring is typically performed in the central, deepest water part of the lake to provide an overall integrative assessment of lake water conditions because this is where sediments from littoral and pelagic zones accumulate through sediment focusing processes (Blais and Kalff 1995). Cores taken from this accumulation zone within lake basins generally provide the most detailed (highest temporal resolution) and continuous paleolimnological records. However, local bays may have separate water quality problems (see the preceding chapter) and therefore require separate sampling and analysis. Deepwater sampling also minimizes wind-driven resuspension of sediments while maximizing the possibility of anoxic conditions that will tend to reduce effects of

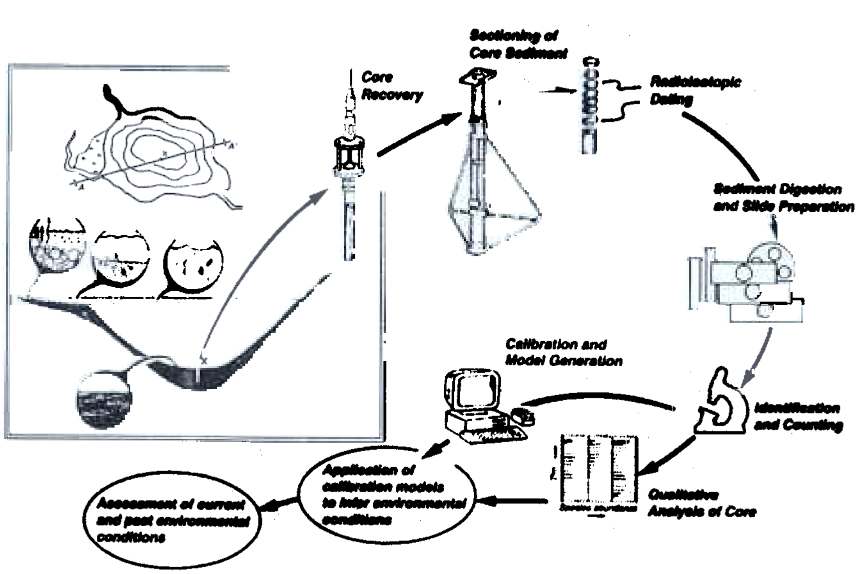

Fig. 1. Outline of the paleolimnological approach to environmental reconstruction (modified from Dixit et al. 1992).

bioturbation, that is the disruption of sediment profiles caused by the burrowing and feeding activity of benthic animals.

In most cases, lake sediments are deposited in a continuous fashion through time, with the most recent material overlying older sediments. Occasionally some problems in stratigraphic integrity occur (e.g., bioturbation, wind-induced turbulence), but these problems can often be identified and assessed. An undisturbed and continuous record of sediments can be retrieved from most lakes using a wide variety of coring techniques, usually including rod-driven piston corers (Livingstone-type), gravity corers (e.g., Kajak-Brinkhurst, Hongve, Glew, Limnos, and many others), or chamber-type samplers (e.g., freeze corers). The advantages and disadvantages of these different types of corers with respect to sediment core collection and extrusion are discussed in detail by Glew et al. (2001).

The sediment chronology is typically established using isotopes. The radioisotopic decay of the naturally occurring ^{210}Pb is now the method of choice to calculate dates of sediment layers over the recent past (up to about 150 years ago), whereas ^{14}C measurements can be used to estimate dates over the millennia. In some cases, a surprisingly high degree of temporal resolution (annual to sub-annual) can be attained in

sediments with annual layers (couplets) called varves. A variety of other geochronological techniques are available including ^{137}Cs and ^{241}Am released by nuclear weapons testing and the nuclear industry (reviewed in Bradley 1999; Appleby 2001).

Sediment analysis – the importance of diatoms

Diatoms (class Bacillariophyta) are an important component of algal assemblages in lakes, comprising a large portion of total algal biomass over a broad spectrum of lake trophic status. They are valuable indicators for water quality monitoring (Stevenson and Smol 2003) and have been used extensively in paleolimnological assessments of changes in lake trophic state (reviewed in Hall and Smol 1999). Diatoms are excellent paleo-indicators because their siliceous cell walls (frustules) which can be identified to species level are generally abundant, diverse, and well preserved in lake sediments. It is common to find several hundred taxa in a single sediment sample, providing considerable ecological information concerning lake eutrophication. Diatoms also respond rapidly to eutrophication and recovery. Their rapid growth and immigration rates and the lack of physical dispersal barriers ensure there is little lag-time between perturbation and response, thereby making them early indicators of environmental change. Moreover, the environmental optima and tolerances of many taxa are generally well known; however, species may respond directly to variables related to lake trophic state, such as phosphorus and nitrogen, but also indirectly to related limnological variables (e.g., stratification patterns, water transparency and depth, ionic concentration and composition, and other water chemistry variables). A major challenge for the paleolimnologist is to determine which environmental variables are related to species assemblages, and to effectively use these inferences in a paleoenvironmental context.

Sediment analysis - other indicators

Given the increased relevance of paleolimnological studies to contemporary limnology and management, greater attention is now being given to organisms other than diatoms, in an effort to broaden the reconstructions to other trophic levels and communities. Holistic or multi-disciplinary approaches (e.g., diatoms, chrysophytes, algal pigments, zooplankton, benthic invertebrates, macrophytes [via plant macrofossils such as leaf tissue]) used in conjunction with transfer function techniques offer a broader perspective of the response of lakes and rivers to disturbance. For example, it is now possible to infer past fish population structure from aquatic insect and zooplankton remains (e.g., Uutala 1990; Jeppesen et al. 1996) and address the problem of historical trophic interactions. The application of the different indicators to the reconstruction of the trophic state of a lake is outlined in detail in Smol et al. (2001a,b).

In addition to the various biological indicators, a wide range of physical and geochemical techniques are available to study the inorganic fraction of lacustrine and riverine sediments (reviewed in Last and Smol 2001). The sedimentary (e.g., particle size, loss-on-ignition or organic matter content), magnetic (e.g., magnetic susceptibility) and geochemical properties (including elemental and isotopic geochemistry) of sediments can yield a wealth of information on the paleolimnology of freshwater ecosystems. For example, bulk organic carbon (^{13}C) and nitrogen (^{15}N) stable isotopes as well as elemental C and N have been employed by Köster et al. (submitted) to study the impacts of anthropogenic activities (including forest clearance and railroad construction in the watershed) on the nutrient balance of New England (USA) lakes. In addition, the isotopes of various metals, such as lead and mercury, can also be used to track pollution sources. The recent introduction of near-infrared spectrometry to paleolimnological studies has allowed for more extensive examination of the chemical and biological constituents of sediments (reviewed in Korsman et al. 2001).

Transfer functions

Paleolimnological interpretations of changes in the physical and chemical conditions of lakes can be made qualitatively and/or quantitatively. Although quantitative inferences are clearly preferred, there is little point in attempting to quantify a weak environment-species relationship. Qualitative interpretations, however, are still very important in many studies, and should not be dismissed as of secondary importance.

Quantitative interpretations are based on the present-day ecological characteristics of algal species (i.e., their optima and tolerances) that have been estimated from their contemporaneous distributions with respect to limnological variables. Inferring the value of, for example, past phosphorus concentrations from fossil diatom remains preserved in lake sediments involves a two-step process. First, the relationship between diatom distribution and contemporary phosphorus is modelled using surface sediment 'calibration' or 'training' sets that are the most powerful methods to determine these relationships (e.g., Birks 1998). The basic approach is to choose a suite of study lakes (typically between 50 to 80, but usually the more the better) that span the limnological gradients of interest. From each study lake, the biological assemblages (e.g., diatom valves) preserved in the surface sediments (usually top 0.5 to 1.0 cm, representing the last few years of sediment accumulation) are identified and enumerated. These sediments provide an integrated sample, in space and time, of the taxa that have

accumulated over the previous few years. From each study lake, environmental data, consisting of present-day physical, chemical, and biological variables that are likely to be ecologically important, are also collected. Due to logistic constraints, these data are often based on "spot" measurements from a single visit to the study sites. A number of multivariate statistical techniques can then be used to determine which environmental variables are most highly related to the biological assemblages. Variables that account for a significant and independent proportion of the variation in the biological assemblages will normally result in strong reconstruction models (Birks 1998). From these data, an inference model or transfer function is constructed, which is then used in a second step to infer, with known errors, environmental variables of interest from the fossil diatom assemblages (Fig. 1).

In paleolimnology, weighted averaging (WA) has become the most popular method for solving these two steps. WA combines ecological plausibility with simplicity and empirical predictive power; it is based on the non-linear, unimodal model of species response which is observed for many diatom taxa, and has lower prediction errors in comparison with other techniques. Given its superior performance, WA has been used to derive phosphorus transfer functions for a number of regions in North America and Europe that have been used to generate quantitative historical total phosphorus (TP) reconstructions (e.g., Fritz et al. 1993; Hall and Smol 1999; Anderson and Odgaard 1994; Bennion et al. 1996; Köster et al. submitted). Pan and Stevenson (1996) developed a diatom-TP inference model for wetlands in western Kentucky (USA), whereas Christie and Smol (1993) produced a transfer function for estimating TN concentrations from diatoms in southeastern Ontario (Canada) lakes. More recently, weighted averaging partial least squares regression (WA-PLS; ter Braak and Juggins 1993; Bennion et al. 1996) has been developed to take into account the residual correlations in the species data due to the effects of unmodelled or nuisance variables, thereby improving the predictive power of the WA coefficients (optima and tolerances) derived from the training sets. Bennion et al. (1996) provide an application of WA-PLS to infer lake eutrophication in southeast England, and discuss the merits of this technique. A comprehensive review by Birks (1995) provides information concerning the basic biological and statistical requirements of quantitative reconstruction procedures, as well as methods for assessing their ecological and statistical performance.

It is important to point out that the environmental optima and tolerances that paleolimnologists are estimating for indicator organisms from surface sediment "calibration" or "training" sets represent empirical relationships. The latter document the distributions and abundances of indicators with respect to the particular environmental and ecological conditions that exist in the study region. Different ecosystems and study regions will have different selection pressures, and therefore the environmental optimum and tolerance determined for a given species in one specific study region will not necessarily be identical to the optimum and tolerance estimated for the same taxon in another calibration data set. Also, given the strong seasonality of planktonic diatoms (e.g., Reynolds 1984) as well as their environment, weighted averaging models based on samples at a single time of year may yield statistical relationships that do not reflect the actual conditions during growth. Paleolimnologists recently have made efforts to improve calibration data sets by comparing the performance of models developed for different seasons as well as for different ecological components (planktonic versus periphytic) of the diatom communities (e.g., Bradshaw et al. 2002; Köster et al. submitted).

Paleolimnology of a Eutrophic Lake

Lake St-Augustin is a small lake in southern Québec (area = 0.7 km^2; Z_{max} = 6.1 m; Z_{av} = 3.5 m) and a popular site for summer and weekend boating, swimming and other recreational activities. It lies some 20 km from the center of Québec City, but as the city has expanded this area has become a small but rapidly growing commuter satellite to the greater metropolitan region. This period of residential development also appears to have coincided with a rapid deterioration in water quality. During intermittent summer stratification the bottom waters of the lake become anoxic (Fig. 2), and blooms of cyanobacteria dominated by *Aphanizomenon* and *Microcystis* now regularly occur each summer and fall (M. Valentine Bouchard et al. unpublished data). These blooms in the years 2001 and 2002 resulted in the municipal closure of the lake to water contact sports and to fishing for several weeks. No long term environmental data are available for this lake, but it was of importance to know the history of deterioration of the lake and whether this was entirely a consequence of the expansion of the residential population.

A paleolimnological approach towards understanding the water quality trend in Lake St-Augustin was adopted by Roberge et al. (2002). A core was obtained from the lake at its deepest site and split into 0.5 cm subsamples. These were then dated by ^{210}Pb and analysed for their content and species composition of fossil diatoms. The surficial sediments were brown-olive in colour and flocculent, to a depth of 15 cm. At greater depth, the sediments were darker and more compact with a higher proportion of clay. There were conspicuous populations of red-pigmented oligochaetes, probably of the pollution-tolerant genus *Tubifex*, in the surficial 5 cm of sediment. The dating of the

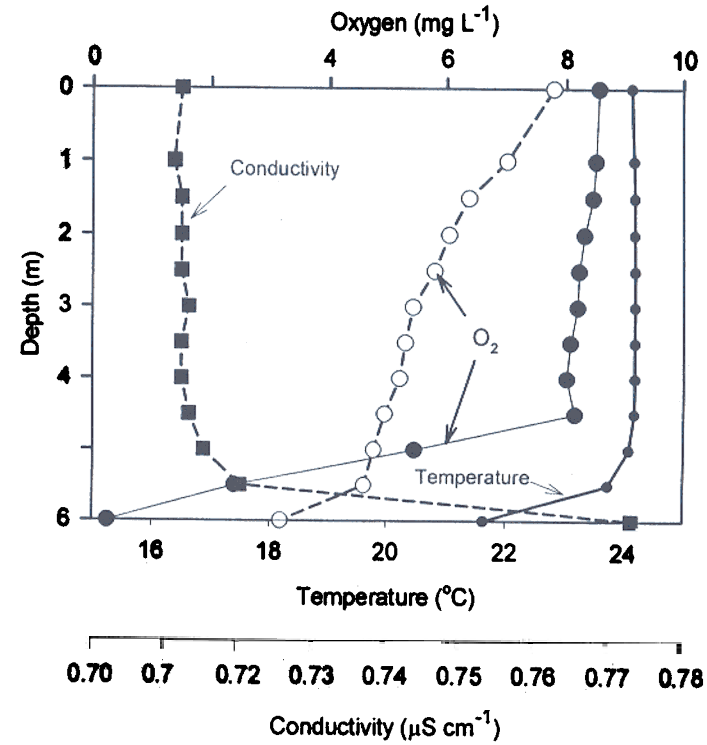

Fig. 2. Intermittent mixing, stratification and anoxia in Lake St-Augustin (Martin Bouchard Valentine et al. unpublished). The closed symbols are for 22 August 2002 (10h00) at the end of a period of stratification. Note the small temperature difference near the bottom of the profile and evidence from the conductivity profile of solute release from the sediments. The open symbols are for 23 August 2002 (10h00), for oxygen after storm-induced mixing.

core showed that the maximum depth of 31 cm corresponded to a date of 240 years before the present. The diatom analysis of the sediment core revealed 132 species, with substantial changes in community composition down the core indicating periods of major change in the nutrient status of the lake over the last two centuries (Fig. 3).

A period of slowly changing limnological conditions extended from 1760 (the date for the bottom of the core) to 1900. The community was dominated by centric diatom taxa such as the planktonic *Aulacoseira ambigua* and *Cyclotella pseudostelligera* (Fig. 3, zone 1) that indicated relatively good quality, oligo-mesotrophic conditions. There was a reduction over this period in some taxa such as the elongated form of

A. ambigua and slow rise in the proportional abundance of others such as the small benthic *Fragilaria pinnata*, suggesting the gradual onset of anthropogenic effects during this initial stage of human colonisation, forest use and land development (nearby Québec City was founded in 1608).

A substantial change took place over the period 1900-1950 (Fig. 3, zone 2), a period of major decline in *A. ambigua* and *Cyclotella* spp., sustained importance of *F. pinnata*, and the appearance of *Stephanodiscus hantzschii*, a small centric diatom species that is indicative of strongly polluted conditions. This would have corresponded to a period of major farm expansion and agricultural development of the catchment. A third abrupt change characterized the transition to post-World War II conditions (late 1940s to late 1970s; Fig. 3, zone 3). At this time the new species that had arrived in the previous period such as *Asterionella formosa* and *Fragilaria crotonensis* became important subdominants, and S. *hantzschii* accounted for up to 45% of the total counts. These observations imply greatly accelerated enrichment, and correspond to the post-war intensification of agriculture and the massive increase in fertiliser application that occurred in many parts of the world at that time.

The final stage in the sediment record is for the period late 1970s to the present and shows co-dominance by the pollution-tolerant taxa *F. crotonensis* and S. *hantzschii* (Fig. 3, zone 4). This period corresponds to the major expansion of residential developments and road construction within the lake's catchment, including a major highway. The increased occurrence of (exotic) salt-tolerant species in recent sediments reflects the inwash of salts used for the de-icing of roads during the winter months. These observations show that the degradation of Lake St-Augustin is the result of a long history of anthropogenic impacts, and that the ultimate restoration of this waterbody must take a similarly long-term perspective. In future paleolimnological studies of this lake it will be of great interest to identify the period of onset of cyanobacterial blooms given that these are the primary water quality concern. One approach towards this is the use of pigment markers in the sediments, as applied, for example, to lakes in the Canadian Prairies (Hall et al. 1999).

Fig. 3. Diatom analysis of a dated sediment core from Lake St-Augustin (... Roberge et al. 2002).

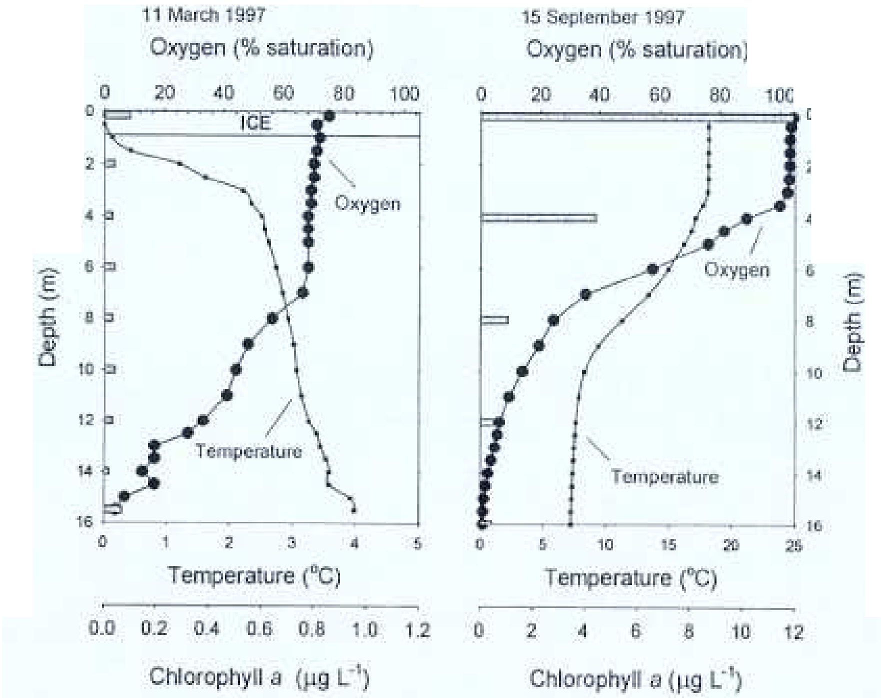

Fig. 4. Water column profiles in Lake St-Charles at the end of winter stratification under the ice, and a the end of summer stratification (modified from Tremblay et al. 2001). The bars represent Chlorophyll a concentrations.

late 1990s showed that this reservoir was showing signs of enrichment, with complete depletion of bottom water oxygen (anoxia) in the deepest part of the lake in late summer and late winter (Fig. 4). Moreover, some local residents believed that the lake was rapidly deteriorating in quality.

In order to estimate the extent of recent changes in trophic status and to identify critical periods of past anthropogenic disturbances, a paleolimnological analysis of Lake St-Charles sediments was undertaken in 1997 by Tremblay et al. (2001). Quantitative estimates of past total phosphorus (TP) concentrations in the water column of Lake St-Charles were obtained by applying a diatom-TP reconstruction model developed for 54 lakes located in south-eastern Ontario (Canada) on fossil diatom assemblages from a 28 cm long sediment core. The timing of changes in the fossil diatom record was estimated by ^{210}Pb dating. The study revealed changes in fossil diatom assemblage composition during the past ca. 150 years (Fig. 5), with the most striking biological and physico-

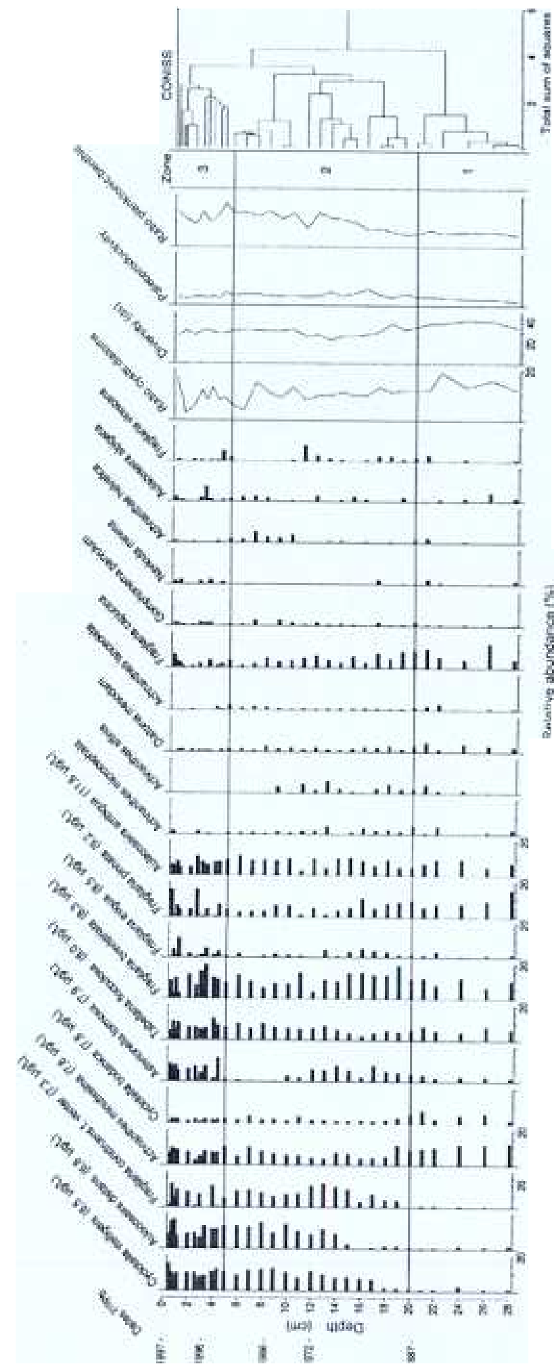

Fig. 5. Diatom analysis of a dated sediment core from Lake St-Charles (modified from Tremblay et al. 2001).

chemical changes occurring immediately after 1934. This date coincides with the construction of a dam, which raised the lake water level by 1.5-2 m. This modification was accompanied by significant shifts in diatom community structure, especially in the planktonic/benthic ratio (with increases in planktonic diatoms *Cyclotella stelligera* and *Aulacoseira distans*), and by changes in the physico-chemical characteristics of the sediments. Paleoproductivity increased at the same time, but remained more or less stable following conservation efforts between 1950 and 1970 (e.g., construction of a sewage treatment system).

The fossil diatom community structure indicates that mesotrophic conditions prevailed during the recent history of Lake St-Charles, and that diatoms typical of eutrophic conditions never became established in the lake. The diatom-inferred quantitative reconstruction of lake water total phosphorus (Fig. 6) revealed a slight decrease in total phosphorus over time, from close to 17 $\mu g \cdot L^{-1}$ prior to 1887 to about 13 $\mu g \cdot L^{-1}$ in recent times.

The fossil diatom analyses indicate that Lake St-Charles has not experienced significant recent changes in trophic status due to increased human activities in its drainage basin. However, our geochemical analyses show a sharp rise in metal concentrations (especially Fe, Mn, Cu, Pb and Zn), beginning in the late 19th century, reaching a plateau by the late 1970s (Fig. 7), which may be attributed to increased atmospheric pollution since the beginning of intense human colonization in the lake's catchment and surrounding areas. This in combination with the advanced mesotrophic status of the lake indicates the ongoing need for careful management of the watershed to prevent further changes in this important urban freshwater resource.

It will of interest in the future to determine at what point in time the bottom waters of Lake St-Charles became anoxic. One approach with considerable promise is the use of chironomids as paleo-indicator organisms. Some of these species have relatively narrow tolerances and require oxygenated conditions while others can tolerate low oxygen and anoxic conditions. Moreover, the head capsules of these insect larvae are relatively resistant to decomposition and therefore remain well preserved in the sediments (see Smol 2002). This approach has been applied with success to lakes in the Canadian prairies where the results showed that anoxic bottom-water conditions occurred well before the arrival of European settlers, and that the lakes were naturally eutrophic (Hall et al. 1999).

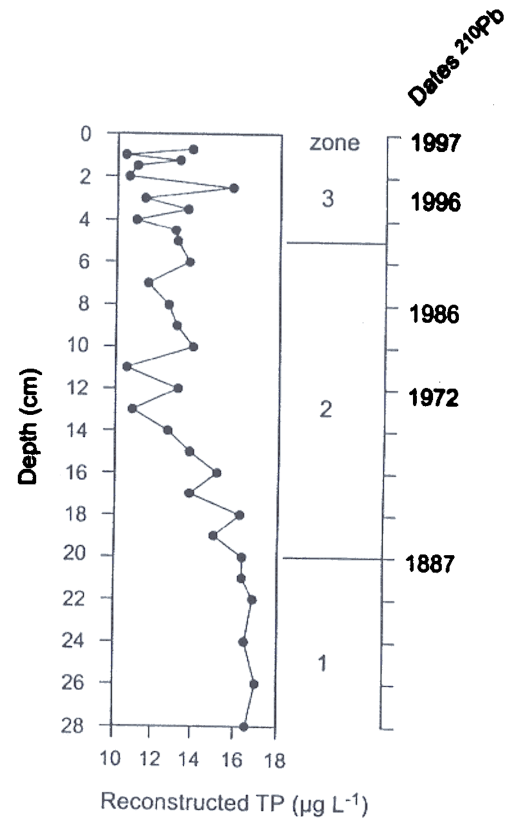

Fig. 6. Reconstructed total phosphorus concentrations in the surface waters of Lake St-Charles, determined from the application of a TP transfer function to the sediment diatom record (modified from Tremblay et al. 2001).

Paleolimnology of a Large River Ecosystem

The St-Lawrence River runs 500 km from Lake Ontario to the sea and is a major resource for navigation, industry, and agriculture. Additionally, it is the drinking water supply for almost half the population of the province of Québec, and is a rich ecosystem with a diversity of wildlife habitats (Vincent and Dodson 1999 and references therein). The river has been severely impacted over the course of the 20th century by industrial and other human activities. Remediation work began in the 1970s, and in the 1980s and 90s major efforts were undertaken to curb the pollution by major industries. Are these efforts resulting in improvement, and how far is the present-day environment from

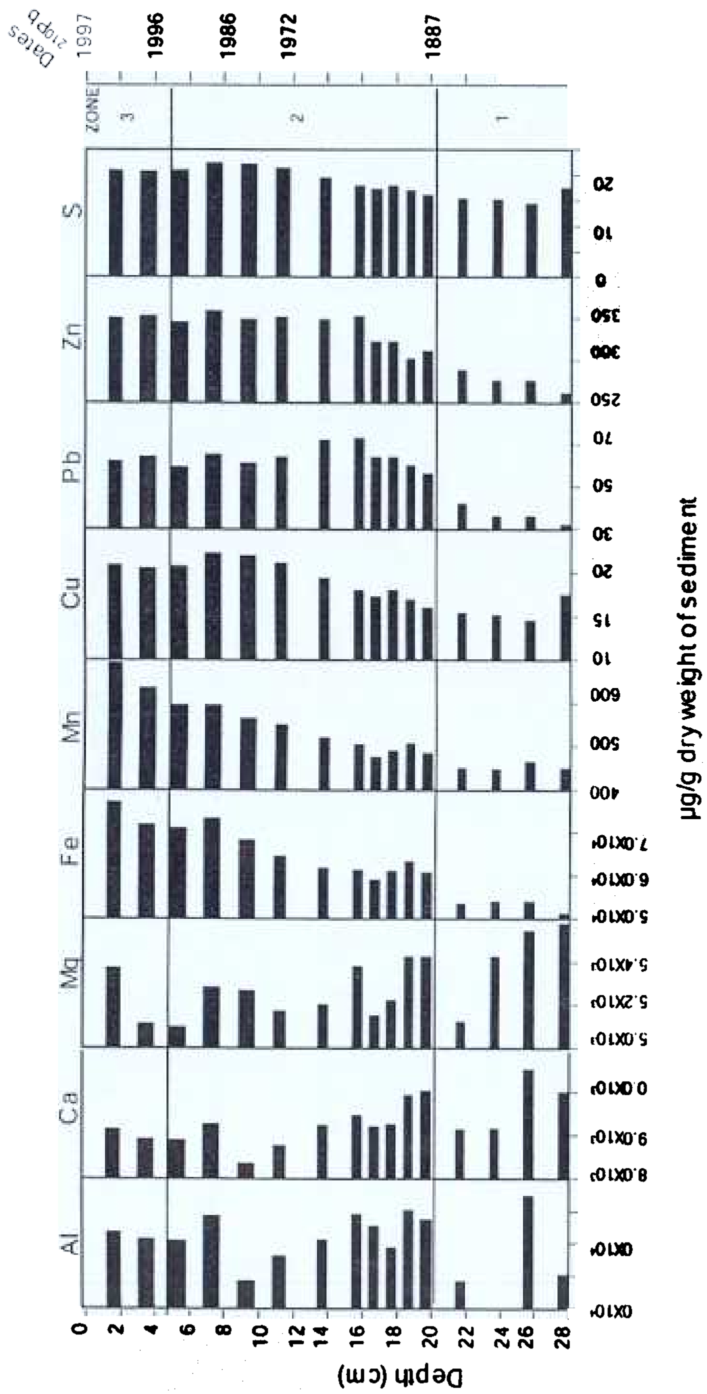

Fig. 7. Concentration of metals and sulfur in the dated sediment core from Lake St-Charles (modified from Tremblay et al. 2001).

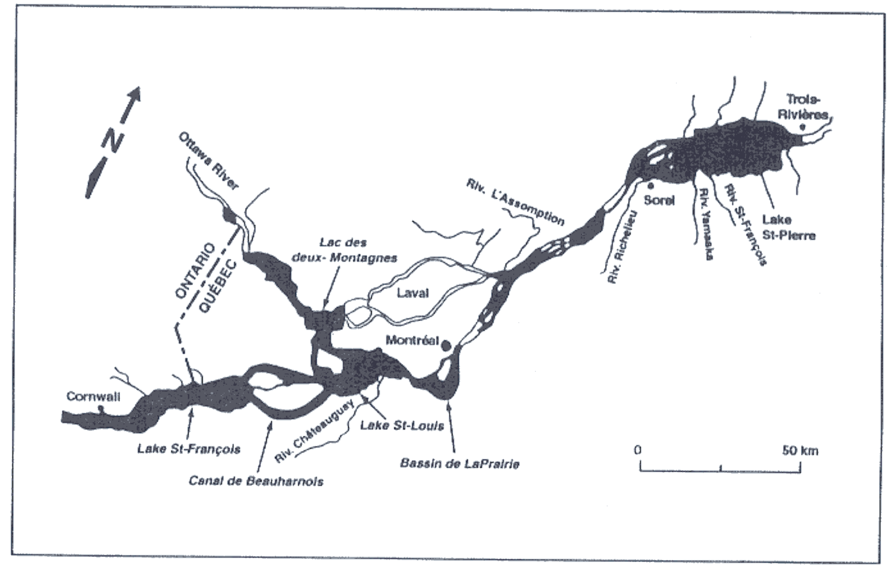

Fig. 8. The fluvial lakes of the St Lawrence River.

natural baseline conditions?

A problem in applying paleolimnological methods to river ecosystems is that fast flowing currents preclude the deposition of sediments, and flood events can completely scour the stream or river bed (Smol 2002). Furthermore, rivers tend to be well-oxygenated and large benthic populations of animals can result in substantial bioturbation. Despite these limitations, sediment cores have been successfully obtained from several parts of the St-Lawrence River, especially the more slowly flowing fluvial lakes (Fig. 8).

A detailed geochemical analysis was undertaken of a ^{210}Pb-dated sediment core from Lake St-Louis, immediately upstream of Montréal (Table 1; Carignan et al. 1994). This analysis showed how very high concentrations of organic contaminants were present in the river in the late 1950s and 60s, and dropped by a factor of 5-10 by 1990. These encouraging signs of improved water quality are also evident from the analysis of trace metals, with substantial reductions in cadmium, copper, lead and zinc. On the other hand, changes in chromium and nickel levels were relatively minor. Furthermore, concentrations of all metals still lay 2-7 times above the background values from pre-industrial strata indicating considerable room for ongoing improvement. These analyses

Table 1. Contamination of sediments in Lake Saint-Louis, St-Lawrence River. The data are compiled from the text and Fig. 6 of Carignan et al. (1994). Pre-industrial values are for the bottom 35-45 cm of a sediment core, > 130 years before present, containing 1.1% organic carbon. The metal values are in ppm and the organic contaminant values are in ppb.

Contaminant	Pre-industrial	Max. during the 1960s	1990
Trace metals			
Cd	0.15	3.5	1
Cr	62	140	120
Cu	17	70	48
Ni	32	70	60
Pb	15	72	38
Zn	78	750	260
Organic contaminants			
PCB #118	0	10	2
Mirex	0	0.8	0.1
DDD	0	8	0.2

also draw attention to the dangers of dredging sections of the St- Lawrence River which could result in resuspension and remobilization of sediments that were heavily contaminated in the middle of last century. Additional paleolimnological work has been undertaken in the St-Lawrence fluvial lakes to reconstruct changes in the riverine algal communities and to examine changes in macrophyte (water weed) biomass (Reavie et al 1998). The results from Lake St-François sediments indicated a marked shift towards high macrophyte populations from the 1930s onwards. Eutrophic diatom taxa were present at their highest proportional abundance during the middle of last century, and then showed some decline in importance up to the end of the record (1990) indicating a recent improvement in water quality and a positive response to rehabilitation and control strategies. There were substantial differences between the paleolimnological records from Lake St-François and Lake St-Louis, indicating the heterogeneous nature of large river ecosystems and the need to consider local variability.

Conclusions

In this chapter, we have provided some of the many examples of how paleolimnological studies based on fossil diatoms and geochemical analysis can be used as powerful tools for eutrophication research and management. The historical perspective allows the assessment of natural variability and the establishment of baseline or pre-disturbance water chemistry conditions as targets for lake rehabilitation. The past decade was largely devoted to developing and refining diatoms as quantitative bioindicators of lake eutrophication. Current research includes assessing how a detailed knowledge of local conditions, for example the seasonal dynamics of the biota and their limnological environment, can be used to improve the application of transfer functions and further refine the interpretation of quantitative paleolimnological records.

Studies of diatoms alone do not allow a full assessment of complex food-web interactions in lakes and rivers, but fortunately there are many other aquatic and terrestrial biota that leave fossil remains in lake sediments (Smol 2002). For example, chironomids have been used to monitor deep-water oxygen levels (Quinlan et al. 1998), and in conjunction with diatoms they will provide a better understanding of the relationships between changes in upper and lower strata of the water column during eutrophication. Fossil pigments (including the remains of nitrogen-fixing cyanobacteria) and diatoms provide a useful measure of the biomass of all major algal groups, as well as total algal biomass (Leavitt and Hodgson, 2001). The combined use of biogenic silica analysis (Conley and Schelske 2001), diatoms, and fossil pigments may help clarify the relative roles of Si, P and N limitation during eutrophication. The combined application of these various bio-indicators and geochemical methods in multi-disciplinary studies will greatly strengthen our ecological understanding of lake eutrophication processes, as well as provide a set of powerful tools for water quality monitoring and management.

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