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APPLIED ISSUES

# Are diatoms good integrators of temporal variability in stream water quality?

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**SUMMARY**

1. Although diatoms have been used for many decades for river monitoring around the world, studies showing evidence that diatoms integrate temporal variability in water chemistry are scarce.
2. The purpose of this study was to evaluate the response of the Eastern Canadian Diatom Index (IDEC: Indice Diatomées de l'Est du Canada) with respect to temporal water chemistry variability using three different spatio-temporal data sets.
3. Along a large phosphorus gradient, the IDEC was highly correlated with averaged water chemistry data. Along within-stream phosphorus gradients, the IDEC integrated phosphorus over various periods of time, depending on the trophic status of the site studied (Boyer, Nicolet or Ste. Anne river) and variability in nutrient concentration.
4. In the Ste. Anne River, where nutrient concentrations were low and generally stable, an input of phosphorus induced a rapid change in diatom community structure and IDEC value within the following week. In the mesotrophic Nicolet River, the observed integration period was approximately 2 weeks. Diatom communities in the eutrophic Boyer River appeared to be adapted to frequent and significant fluctuations in nutrient concentrations. In this system, the IDEC therefore showed a slower response to short term fluctuations and integrated nutrient concentrations over a period of 5 weeks.
5. Our results suggest that the integration period varies as a function of trophic status and nutrient concentration variability in the streams. Oligotrophic streams are more sensitive to nutrient variations and their diatom communities are directly altered by nutrient increase, while diatom communities of eutrophic rivers are less sensitive to nutrient fluctuations and major variations take a longer time to be integrated into index values.
6. The longer integration period in the eutrophic environment may be attributed to the complexity of the diatom community. The results from this study showed that the diversity and evenness of the communities increased with trophic status.

*Keywords*: benthic diatoms, biological integrity, streams, temporal variability, water quality

## Introduction

Biological monitoring provides a direct measure of ecological integrity by using the response of biota to environmental change (Karr, 1991). Among

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biota used, benthic diatoms are excellent organisms because they lie at the base of aquatic food webs and are among the first organisms to respond to environmental changes (Lowe & Pan, 1996; McCormick & Stevenson, 1998). They have short life cycles enabling them to respond quickly to environmental change, are rich in species compared to other aquatic organisms and have a wide distribution across ecosystems and geographic areas allowing a continuous spatial distribution across regional monitoring (McCormick & Cairns, 1994; Stevenson & Pan, 1999).

Europe has a long history of using diatoms for biological monitoring of stream water quality (e.g. Butcher, 1947; Fjerdingstad, 1964), and a myriad of regionally scaled biocenotic indices, such as the Specific Polluo-sensitivity Index (IPS) (Coste, 1982), the Diatom Biological Index (IBD) (Lenoir & Coste, 1996; Prygiel & Coste, 2000) and the Trophic Diatom Index (Kelly & Whitton, 1995), have been developed. Several recent studies carried out in Canada and the United States have also shown the potential use of diatom communities as indicators of water quality (e.g. Hill *et al.*, 2000; Leland & Porter, 2000; Winter & Duthie, 2000; Potapova & Charles, 2002; Wang, Stevenson & Metzmeier, 2005). In Canada, the Eastern Canadian Diatom Index (IDEC: Indice Diatomées de l'Est du Canada) was recently developed as a tool for biological monitoring of stream water quality, and to supplement traditional stream monitoring protocols (Grenier *et al.*, 2006; Lavoie *et al.*, 2006).

Numerous publications mention the response of diatoms to environmental variations over a short period of time (e.g. Stevenson & Pan, 1999), and their ability to integrate temporal variability in water chemistry (e.g. Metcalfe-Smith, 1994; Parr, 1994). However, there are few studies showing that diatom-based assessment protocols, in fact, provide an integrated assessment of stream water quality. Furthermore, given observed temporal variation in nutrient concentrations, the time scale over which diatoms integrate the system's response is poorly understood. Many studies have shown good relationships between diatom-based indices and water chemistry (e.g. Descy & Coste, 1991; Kelly & Whitton, 1995; Wu & Kow, 2002; Lavoie *et al.*, 2006), but have not explicitly dealt with the integration ability or the response time following a change in the environment. A recent study conducted by Taylor, Janse van Vuuren & Pieterse (2007) suggests that diatom-based indices in general have the best correlation with average chemical data for a 1-month period, starting 6 weeks before diatom sampling. On the other hand, Prygiel & Coste (1993) showed that the best correlations between diatom indices and chemical parameters were obtained using simultaneous or average chemical analyses for certain parameters, whereas the best correlations were noted with chemical analyses carried just before diatom sampling for other parameters. However, the water chemistry data set in Prygiel & Coste (1993) (monthly sampling) did not allow for the evaluation of temporal integration of water quality by diatoms over a shorter time frame. The purpose of this study was to evaluate the response of a diatom-based index (IDEC) with respect to temporal water chemistry variability using three different spatio-temporal data sets.

## Methods

This study was based on three chemistry data sets characterized by different spatio-temporal scales. The first data set was generated from a high frequency chemistry sampling campaign (two to eight measurements per week during 20 weeks) of one site in the Boyer River (Québec, Canada) (Fig. 1). The second data set was generated from an intermediate frequency chemistry sampling campaign (one measurement per week during 14 weeks) of two sites, one in the Nicolet River and one in the Ste. Anne River (Fig. 1). According to Dodds, Jones & Welch (1998), the Ste. Anne, Nicolet and Boyer rivers may be classified as oligotrophic, mesotrophic and eutrophic streams respectively. The different characteristics of these sites were necessary to test the sensitivity of the IDEC in different environmental conditions. The last data set was generated from a large scale data base that consisted of measurements from 126 sites in Québec (Fig. 1) following a low frequency chemistry sampling campaign (one measurement per month during 3 years).

### *High frequency data set*

The first data set (high frequency chemistry sampling) was generated from Boyer River (Boyer Nord), sampled from May to September 1999 (Fig. 1). The Boyer River is located in the St Lawrence Lowlands and is a highly impacted stream with 60% of its catchment

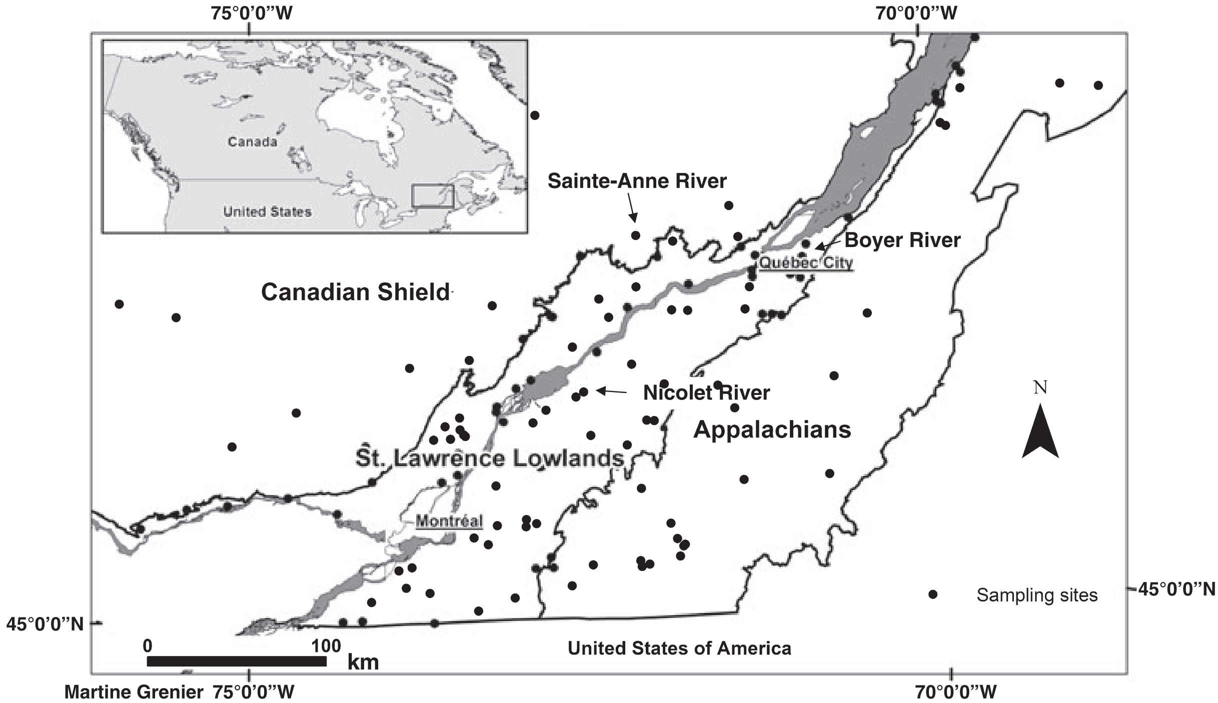


**Fig. 1** Sites sampled for the development of the Eastern Canadian Diatom Index and for the development of the low frequency sampling data set. The sampling sites of the intermediate (Nicolet and Ste. Anne River) and high (Boyer River) frequency sampling data sets are identified on the map.

occupied by farmlands. Total phosphorus (TP) measurements for the Boyer River were obtained from an automated sampling station operated by the Ministry of the Environment of Québec (sampling frequency varied as a function of discharge). Analytical method and detection limits are described in Hébert (1999). Diatom samples were collected from the Boyer River on a bi-monthly basis from May until September 1999.

### *Intermediate frequency data set*

The second data set (intermediate frequency chemistry sampling) was generated from the Nicolet and Ste. Anne (Bras du Nord) rivers, sampled from July to September 2005 (Fig. 1). The sampling site in Ste. Anne River was located on the Canadian Shield, while the sampling site for the Nicolet River was located in the St Lawrence Lowlands. The catchment of Ste. Anne River consists of 95% forested areas, whereas agricultural activities occupy 43% of Nicolet River's catchment. Diatom and water samples taken for nutrient analysis were collected from the Ste. Anne and Nicolet rivers on a weekly basis from July until September 2005. Water samples were immediately frozen and analysed for TP concentrations at the Université du Québec à Trois-Rivières (Québec). TP was determined by the blue molybdate technique after persulphate oxidation (Valderrama, 1981).

### *Low frequency data set*

The third data set was generated from samples collected at numerous sites in Québec on a low frequency basis. This data set was used to develop the Eastern Canadian Diatom Index (IDEC) (Lavoie *et al.*, 2006). A total of 204 diatom samples were collected during the autumn of 2002 and 2003 at 126 sampling locations distributed along 32 streams in the St Lawrence River Basin (Fig. 1). Most sites were visited twice for diatom sampling, once during the autumn of 2002 and once during the autumn of 2003. A few sites were sampled only once, either in 2002 or 2003. The sampling sites were distributed within three ecoregions: the Canadian Shield, the St Lawrence Lowlands and the Appalachians. The Canadian Shield catchments are mostly covered by boreal forests, and are considered to be less impacted. The St Lawrence

Lowlands are characterized by intensively farmed areas, large industrial centres and are inhabited by most of Québec's population. These catchments exhibit a gradient from slightly impacted to very impacted streams. The catchments located in the Appalachians are also impacted by farming, but to a lesser extent. Water samples were collected and analysed on a monthly basis by the Ministry of the Environment of Québec as part of the stream monitoring programme. The following parameters were analysed by the Ministry of the Environment of Québec: TP, total dissolved nitrogen (TDN), chlorophyll *a* (Chl *a*), pH, conductivity (CON), turbidity (TUR) and coliforms (CF).

### *Diatom sampling and analysis*

Benthic diatom communities of the intermediate and low frequency data sets were sampled by scraping the top surface of rocks using a toothbrush as described by Kelly *et al.* (1998). Following the recommendation of Winter & Duthie (2000), one composite sample of five rocks per site was collected within a *c.* 5 $m^2$ area. Sampling depth varied from 20 to 50 cm, depending on turbidity and water level. Algae were collected from riffles where possible. The algae collected were preserved with Lugol's iodine and stored until the samples were digested in 30% hydrogen peroxide and mounted onto microscope slides using Naphrax. The diatom communities of the high frequency data set were sampled and processed following a different protocol. Periphyton was scraped from the top surface of a rock using a blade and a brush. The samples were preserved with a solution of 10% paraformaldehyde and glutaraldehyde. The samples were digested using a mixture of 1 : 1 sulphuric and nitric acid and mounted on slides with Naphrax. For all samples, a minimum of 400 valves (Prygiel & Coste, 1993) per slide were counted and identified to species level when possible. Diatom relative abundance was estimated from the counts. Taxonomic identifications generally followed Krammer & Lange-Bertalot (1986, 1988, 1991a,b), Reavie & Smol (1998), Fallu, Allaire & Pienitz (2000), Krammer (2000, 2002, 2003) and Lange-Bertalot (2001).

### *Integration of temporal variability*

The integration of temporal variability was evaluated based on the response of the Eastern Canadian Diatom Index (IDEC) with respect to temporal water chemistry variability. The index value indicates the distance of an altered diatom community from its specific reference community. A high index value represents a non- or least-impacted site while a low index value represents a more heavily impacted site. The integration of temporal variability in water chemistry by diatom communities was first evaluated using the high and intermediate frequency data sets from the Boyer, Nicolet and Ste. Anne rivers. Regression analyses were conducted between IDEC and TP values using SYSTAT (version 10, 2000; Systat Software Inc., San Jose, CA, U.S.A.). TP concentrations were expressed as one-time measurements, 1-week averages, 2-week averages, 3-week averages, 4-week averages and 5-week averages. The high and intermediate frequency data sets did not allow for the integration of TP concentrations over a longer time period. These averages were used in order to determine if the IDEC has a stronger relationship with integrated (averaged) water chemistry than with one-time chemistry measurements, and to estimate the time period over which diatoms can integrate temporal variability in environmental variables. As diatom communities may need time to adjust to environmental conditions, IDEC values may be better correlated to TP concentrations of previous weeks. To account for this potential time lag, another set of correlation analyses were conducted with a time lag of 1 week between IDEC values and TP concentrations. These correlations were also conducted with TP concentrations expressed as one-time measurements or averaged values. Finally, correlation analyses were also conducted with longer time lags (2 and 3 weeks).

For the low frequency chemistry data set, the potential of diatoms to integrate temporal variability in water chemistry was investigated using regression analyses of the IDEC and nutrients (TP and TDN) values. Nutrient concentrations were expressed as: one-measurement, two-measurements (2-month average) and six-measurements (3-year seasonal average). The one-measurement metric corresponds to the one-time chemistry data available for the period prior to diatom sampling. The two-measurement metric is the chemistry averaged over the 2 months preceding diatom sampling (August and September). The six-measurement metric was calculated from the six measurements taken in August and September over a 3-year period (including the year the diatoms were sampled) in order to characterize the average water chemistry conditions during the sampling period (late summer) over multiple years. Although this data set includes low frequency chemistry measurements (monthly basis), it has the advantage of including a large number of sites.

The low frequency data set was also used to evaluate the potential for diatoms to integrate temporal variability using partial canonical correspondence analyses (partial CCAs). Partial CCAs were conducted using the 204 diatom samples collected at the 126 sites in the province of Québec and environmental variables (TP, TDN, CON, pH, TUR, CF and Chla) expressed as: one-measurement, two-measurements (2-month average) and six-measurements (3-year seasonal average). Partial CCAs indicate the percent variance in diatom communities explained by each environmental variable when they are used as the sole constraining variable in the ordination. CANOCO 4.5 (ter Braak & Smilauer, 2002) software was used to execute the partial CCAs.

## Results

### *Water chemistry*

The high and intermediate frequency data sets showed a great variability in TP concentrations (Fig. 2). TP concentrations in the Ste. Anne River were low throughout the sampling season, ranging from 8 to 24 μg P $L^{-1}$. The variability in TP concentrations throughout the sampling season was very significant in the Nicolet River, ranging from 11 to 200 μg P $L^{-1}$. The TP concentrations in the Boyer River were high and varied throughout the sampling season from 30 to 1220 μg P $L^{-1}$. Discharge of each stream varied throughout the sampling season, with peak values observed at the beginning and near the end of the sampling period (Fig. 2). TP concentrations were generally positively correlated with discharge. In the Boyer River, where numerous TP data were available, Fig. 2 showed that TP concentrations increased rapidly following peak discharge events, and that TP levels decreased more quickly than discharge. This phenomenon was particularly noticeable following peak discharge events early and late in the sampling season. Median TP values in the Boyer, Nicolet and Ste. Anne rivers were 130, 46 and 10 μg P $L^{-1}$ respectively.

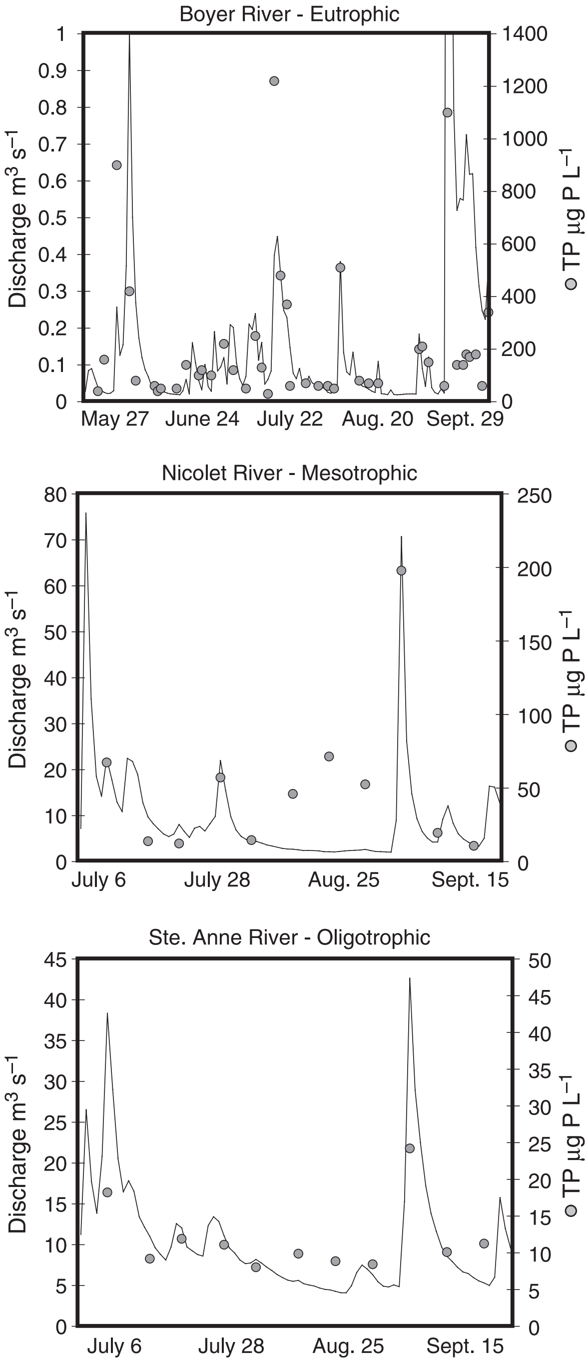


**Fig. 2** Discharges and TP concentrations throughout the sampling season in the Boyer, Nicolet and Ste. Anne rivers.

The low frequency data set showed that the 126 stream reaches selected to develop the IDEC included a wide range of catchment characteristics and showed a great variability in water chemistry. Median values and first and third quartiles for measured water-chemistry variables at the 126 sites are presented in Table 1.

**Table 1** Median values and first and third quartiles for measured water-chemistry variables of the low-frequency data set

| | | Canadian Shield | | | St Lawrence Lowlands | | | Appalachians | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Code | Description | Q1 | Median | Q3 | Q1 | Median | Q3 | Q1 | Median | Q3 |
| TP | Total phosphorus (μg $L^{-1}$) | 14.5 | 17.3 | 19.8 | 25.8 | 50.6 | 131.3 | 21.6 | 24.0 | 35.5 |
| TDN | Total Dissolved Nitrogen (μg $L^{-1}$) | 181.7 | 210.0 | 258.3 | 330.0 | 633.3 | 1353.3 | 274.6 | 410.3 | 560.4 |
| $NH_3$-N | Ammonia (μg $L^{-1}$ N) | 20.0 | 20.0 | 25.0 | 25.0 | 36.0 | 56.7 | 21.5 | 25.0 | 50.4 |
| CHLA | Chlorophyll *a* (mg $m^{-3}$) | 1.9 | 2.5 | 2.8 | 3.4 | 7.3 | 13.9 | 2.8 | 4.2 | 7.9 |
| PH | pH | 7.1 | 7.3 | 7.3 | 7.8 | 8.1 | 8.4 | 7.8 | 8.0 | 8.2 |
| CON | Conductivity (μS $cm^{-1}$) | 28.7 | 37.6 | 69.9 | 159.7 | 273.4 | 393.1 | 135.8 | 163.3 | 233.4 |
| TEMP | Water temperature (°C) | 19.2 | 20.2 | 20.9 | 19.7 | 21.5 | 22.5 | 19.8 | 21.2 | 22.2 |
| $O_2$ | Dissolved oxygen (mg $L^{-1}$) | 8.7 | 9.1 | 9.7 | 8.2 | 9.1 | 10.0 | 8.7 | 9.2 | 9.9 |
| TUR | Turbidity (NTU) | 0.8 | 1.3 | 2.0 | 2.5 | 5.6 | 10.7 | 1.4 | 2.7 | 4.1 |
| SS | Suspended solids (mg $L^{-1}$) | 2.0 | 2.4 | 3.4 | 4.2 | 7.3 | 16.4 | 2.3 | 3.3 | 5.5 |
| CF | Coliforms (UFC 100 $mL^{-1}$) | 22.8 | 43.8 | 85.8 | 122.0 | 277.0 | 1024.0 | 55.7 | 122.6 | 214.7 |
| DOC | Dissolved organic carbon (mg $L^{-1}$) | 4.0 | 4.6 | 5.2 | 4.7 | 6.0 | 7.6 | 3.9 | 5.7 | 6.7 |

The values are shown for each ecoregion.

**Table 2** Relative abundance for some of the most abundant taxa observed in the Boyer, Nicolet and Ste. Anne rivers. For each river, the relative abundance is presented for sampling dates with two of the lowest IDEC values and two of the highest IDEC values

| **Boyer** | IDEC = 17 | IDEC = 16 | IDEC = 28 | IDEC = 29 |
|---|---|---|---|---|
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow | 1 | 4 | 1 | 11 |
| *Cyclotella meneghiniana* Kützing | 2 | 16 | 0 | 7 |
| *Diatoma vulgaris* Bory | 0 | 2 | 0 | 7 |
| *Encyonema lange-bertalotii* Krammer | 1 | 0 | 3 | 16 |
| *Fistulifera saprophila* (Lange-Bertalot & Bonik) Lange-Bertalot | 16 | 1 | 1 | 0 |
| *Gomphonema minutum* (Agardh) Agardh | 0 | 4 | 2 | 6 |
| *Navicula gregaria* Donkin | 9 | 1 | 11 | 2 |
| *Navicula lanceolata* (Agardh) Ehrenberg | 7 | 0 | 8 | 0 |
| *Navicula minima* Grunow | 0 | 16 | 1 | 2 |
| *Navicula subminuscula* Manguin | 3 | 4 | 1 | 4 |
| *Nitzschia palea* (Kützing) W. Smith | 16 | 15 | 0 | 4 |
| *Reimeria uniseriata* Sala *et al.* | 3 | 2 | 23 | 0 |
| **Nicolet** | IDEC = 53 | IDEC = 53 | IDEC = 69 | IDEC = 68 |
| *Achnanthidium minutissimum* (Kützing) Czarnecki | 83 | 29 | 60 | 60 |
| *Cocconeis pediculus* Ehrenberg | 1 | 9 | 9 | 7 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow | 1 | 8 | 1 | 20 |
| *Navicula capitatoradiata* Germain | 0 | 10 | 1 | 1 |
| *Nitzschia palea* var. *debilis* (Kützing) Grunow | 0 | 4 | 0 | 0 |
| *Reimeria uniseriata* Sala *et al.* | 4 | 5 | 16 | 4 |
| **Ste. Anne** | IDEC = 93 | IDEC = 84 | IDEC = 100 | IDEC = 100 |
| *Achnanthidium minutissimum* | 68 | 67 | 5 | 28 |
| *Brachysira microcephala* (Grunow) Compère | 5 | 3 | 1 | 7 |
| *Tabellaria flocculosa* (Roth) Kützing | 6 | 8 | 79 | 48 |

Values are expressed in percentage.

### *Diatom communities and IDEC values*

The intensive diatom sampling in the Boyer, Nicolet and Ste. Anne rivers revealed an important variability in observed diatom community structure. The relative abundance for some of the most abundant taxa observed in the Boyer, Nicolet and Ste. Anne rivers is shown in Table 2. The relative abundance is presented for sampling dates with two of the lowest IDEC values and sampling dates with two of the highest IDEC values. The community structure (relative abundance) differed markedly during the season, even for very similar IDEC values. A difference in stream integrity status between the Ste. Anne, Nicolet and Boyer rivers was indicated by the IDEC values. The IDEC values ranged from 84 to 100 in the Ste. Anne River, indicating a high ecological status throughout the sampling season. In the Nicolet River, the IDEC values ranged from 43 to 73, indicating that the ecosystem integrity varied from moderate to good ecological status during the sampling season. The IDEC values in the Boyer River ranged from 16 to 29, indicating that the ecosystem integrity varied from bad to poor ecological status, depending on the sampling date. Slight variations in IDEC values (<10) were associated with changes in taxa relative abundance, without the disappearance of a taxon or the appearance of a new taxon. On the other hand, more important variations in IDEC values were often associated with appearance or disappearance of taxa. For example, the IDEC value in the Ste. Anne River decreased from 100 to 84 due to a drastic decrease in the abundance of *Tabellaria flocculosa* (Roth) Kützing and an increase in the abundance of *Achnanthidium minutissimum* (Kützing) Czarnecki (Fig. 3). In the Nicolet River, an increase in TP level was followed by a decrease in the abundance of *A. minutissimum*, and an increase of *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow and *Cocconeis pediculus* Ehrenberg over a period of 2 weeks (Fig. 3). These structural changes in the community induced a drop in the IDEC value. This pattern occurred twice during the sampling season. At the end of the sampling season, an important increase in TP concentration, reaching 200 μg $L^{-1}$, co-occurred with an increase in the relative abundance of *Nitzschia palea* (Kützing) W. Smith and *Navicula capitatoradiata* Germain resulting in a drop of IDEC value. *N. palea* and *N. capitatoradiata*, which were also found in the Boyer River, are both tolerant to pollution but to differing extents. In the Boyer river, the relative abundance of certain taxa, such as *Cyclotella meneghiniana* Kützing and *N. palea*, increased following extreme TP levels resulting in a drop in IDEC values. Conversely, the relative proportion of *Encyonema lange-bertalotii* Krammer, *C. placentula* var. *euglypta* and *N. capitatoradiata* decreased following extreme TP levels. For the low frequency data set, IDEC values were calculated for the 204 samples collected in the 126 stream reaches visited during the autumn of 2002 and 2003. Diatom communities varied markedly between the least and the most impacted

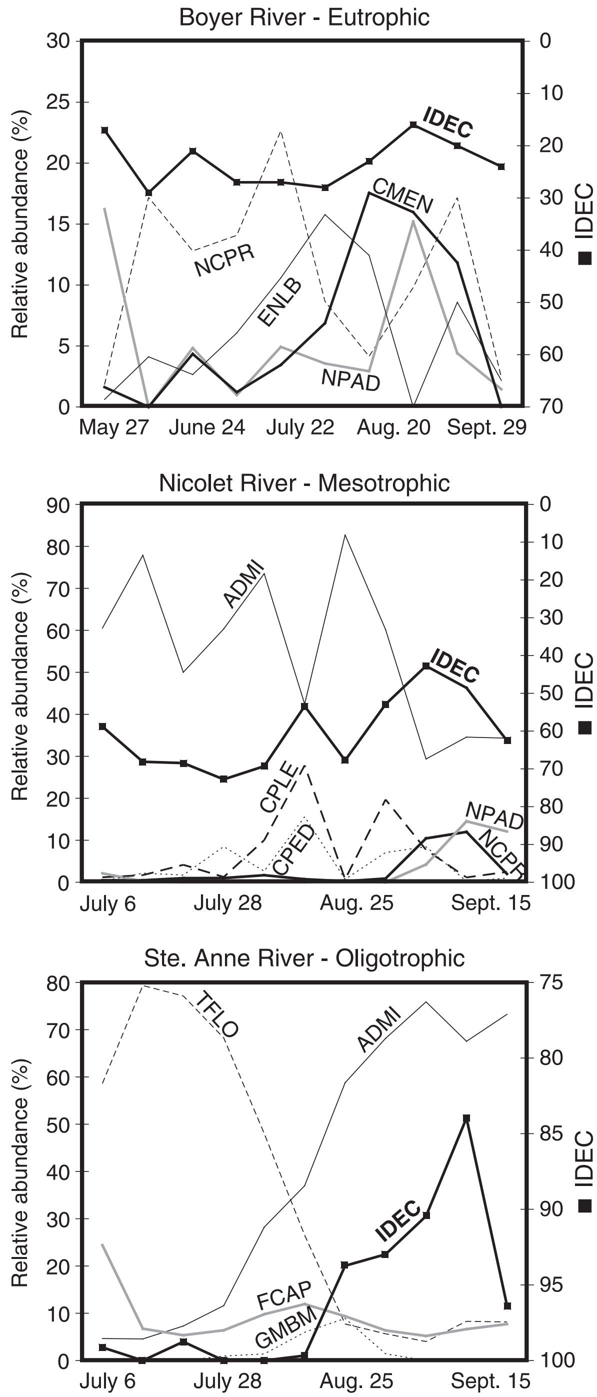


**Fig. 3** Relative abundance variation of some dominant taxa along with IDEC value fluctuation for the Boyer, Nicolet and Ste. Anne rivers. NCPR = *Navicula capitatoradiata*, ENLB = *Encyonema lange-bertalotii*, NPAD = *Nitzschia palea* var. *debilis*, CMEN = *Cyclotella meneghiniana*, ADMI = *Achnanthidium minutissimum*, CPLE = *Cocconeis placentula* var. *euglypta*, CPED = *Cocconeis pediculus*, TFLO = *Tabellaria flocculosa*, FCAP = *Fragilaria capucina*, GMBM = *Gomphonema manubrium*.

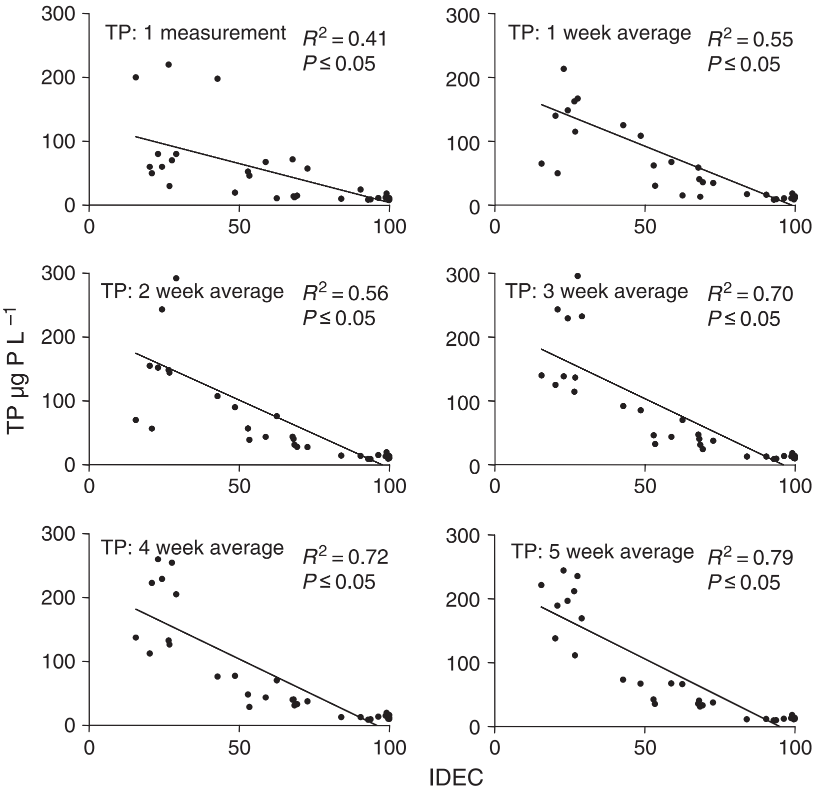


**Fig. 4** Regression analyses between the IDEC values and TP concentrations expressed as one-time measurement and averages (integrated TP) for the Boyer, Nicolet and Ste. Anne rivers ($n$ = 31).

sites. A detailed presentation of the IDEC values in the 204 samples is presented in Lavoie *et al.* (2006).

### *Integration of temporal variability*

Integration of temporal variability in water chemistry was initially evaluated using the high and intermediate frequency data sets from the Boyer, Nicolet and Ste. Anne rivers. Regression analyses were conducted combining the data from the three rivers (Fig. 4). The lowest regression coefficient ($R^2 = 0.41$, $P \leq 0.05$) was observed when IDEC values were regressed against one-time TP measurements. The values of regression coefficients increased when averaged TP concentrations were used, with the highest value ($R^2 = 0.79$, $P \leq 0.05$) obtained when IDEC values were regressed against TP values averaged over the 5 weeks preceding diatom sampling. These results suggest that along a wide phosphorus gradient ranging from 8 to 300 µg P $L^{-1}$, the IDEC was highly correlated with water chemistry data averaged over the weeks preceding diatom sampling.

Correlations conducted independently for each of the three rivers are presented in Table 3. As diatom

**Table 3** Pearson correlation coefficients between the IDEC values and TP concentrations expressed as one-time measurement and averages (integrated TP) for the Boyer, Nicolet and Ste. Anne rivers.

| | Boyer | | | | Nicolet | | | | Ste. Anne | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No lag | 1-week lag | 2-week lag | 3-week lag | No lag | 1-week lag | 2-week lag | 3-week lag | No lag | 1-week lag | 2-week lag | 3-week lag |
| One measurement | −0.12 | −0.21 | 0.40 | 0.06 | −0.56 | −0.46 | −0.20 | 0.10 | −0.18 | **−0.46** | 0.35 | 0.47 |
| 1-week average | 0.73 | −0.54 | 0.06 | 0.05 | −0.76 | −0.49 | −0.10 | 0.40 | −0.31 | 0.08 | 0.55 | 0.53 |
| 2-week average | 0.79 | −0.34 | −0.36 | −0.29 | **−0.81** | −0.46 | −0.06 | 0.13 | −0.04 | 0.25 | 0.62 | 0.69 |
| 3-week average | 0.52 | −0.27 | −0.15 | −0.03 | −0.71 | −0.35 | −0.09 | 0.40 | 0.13 | 0.38 | 0.76 | 0.66 |
| 4-week average | 0.48 | −0.65 | −0.22 | 0.04 | −0.66 | −0.40 | −0.01 | 0.66 | 0.23 | 0.44 | 0.77 | 0.73 |
| 5-week average | 0.25 | **−0.69** | −0.04 | −0.03 | −0.66 | −0.17 | 0.22 | 0.67 | 0.40 | 0.52 | 0.70 | 0.66 |

Values in bold represent the highest negative correlations and are significant ($P \leq 0.05$).

 

communities may need time to adjust to environmental conditions, IDEC values may be better correlated to TP concentrations of previous weeks. To account for this potential time lag, correlation analyses were also conducted with a time lag of one to 3 weeks between IDEC values and TP concentrations. High negative coefficients show that IDEC values decrease as TP increase (ecological status decreases as TP increases). For the Boyer River, the best negative correlation was obtained using TP concentrations averaged over a period of 5 weeks preceding diatom sampling, with a time lag of 1 week between IDEC and TP values. For the Nicolet River, the best correlation was obtained using TP concentrations averaged over a period of 2 weeks preceding diatom sampling, without any time lag between IDEC and TP values. One-time TP measurements, with a time lag of 1 week between IDEC and TP values, produced the best correlation coefficient for the Ste. Anne River.

Temporal fluctuations in TP concentrations and IDEC values are presented in Figs 5–7, along with the moving averages of TP concentrations that showed the best correlations with IDEC values in each of the three rivers. The figures show the variability in TP concentrations when expressed as one-time measurement in the Boyer River (eutrophic) and Nicolet River (mesotrophic), ranging from 30 to 1220 μg $L^{-1}$ and 11 to 200 μg $L^{-1}$ respectively. Although TP levels fluctuated markedly in the Boyer and Nicolet rivers, the IDEC values did not vary as much. As stated before, in the case of the Boyer River, IDEC values show a better fit with TP concentrations averaged over a period of 5 weeks (Fig. 5b). A time lag of approximately 1 week is observed between TP averages and IDEC values. For example, the drop in the IDEC value observed in June occurred 1 week after the first averaged TP peak (notice the inverse IDEC axis). Similarly, the drop in IDEC values observed in August occurred 1 week after the increase in TP averages. In the case of the Nicolet River, IDEC values show a better fit with TP concentrations averaged over a period of 2 weeks (Fig. 6b). No time lag is apparent: low and high IDEC values occurred simultaneously with high and low TP averages. For the Ste. Anne River, IDEC values show a better fit with one-time TP measurements, with a time lag of 1 week (Fig. 7). The major IDEC drop occurred at the end of the season 1 week after the increase in TP concentration. These results suggest that along the within-stream phos-

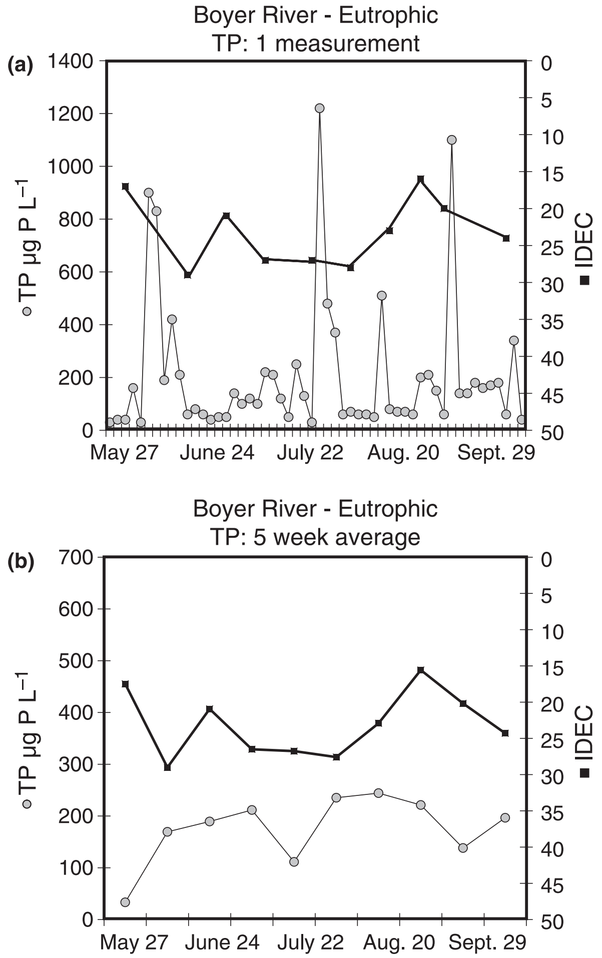


**Fig. 5** Variations in TP concentrations expressed as (a) one-time measurements and (b) 5-week averages and the IDEC values for the Boyer River.

phorus gradient, diatom communities (expressed as IDEC values) integrated phosphorus over various periods of time, depending on the trophic status of the site and the variability in nutrient concentrations.

The low frequency data set was also used to study the ability of the IDEC to integrate temporal variability in water chemistry. However, this data set could not be used to assess short term (<1 month) integration of temporal variability due to the low frequency in chemistry sampling (on a monthly basis). This data set was rather used to compare the portion of the variance in diatom community structure explained by chemistry data expressed as one-time measurements and chemistry data expressed as seasonal averages. The high number of diatom samples (204) in this dataset allowed for this rigorous comparison between chemistry metrics. Partial CCAs showed that the

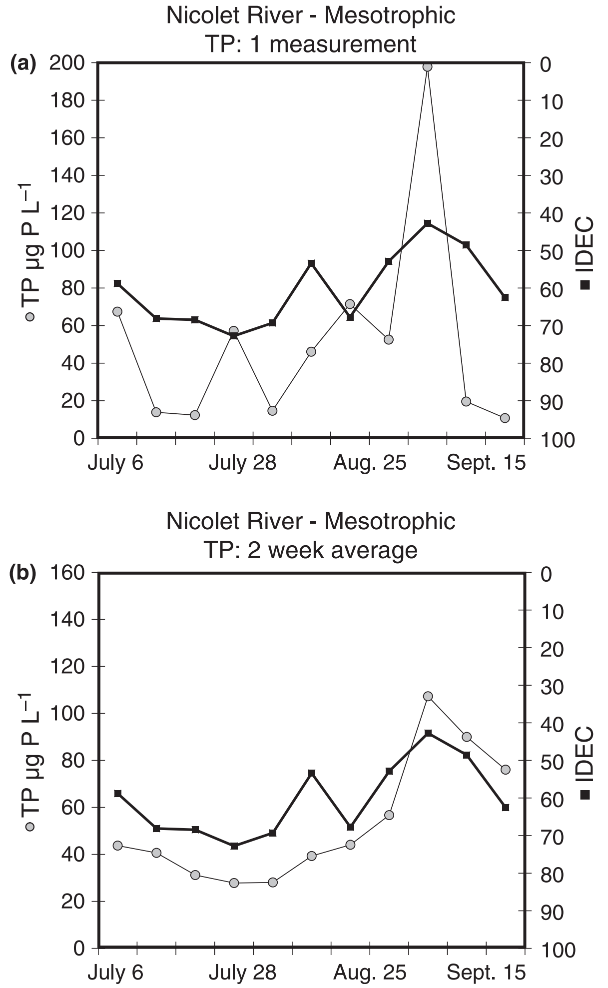


**Fig. 6** Variations in TP concentrations expressed as (a) one-time measurements and (b) 2-week averages and the IDEC values for the Nicolet River.

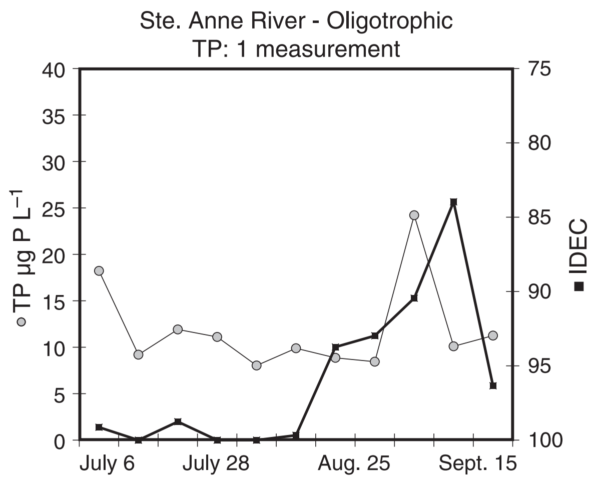


**Fig. 7** Variations in TP concentrations expressed as one-time measurements and the IDEC values for the Ste. Anne River.

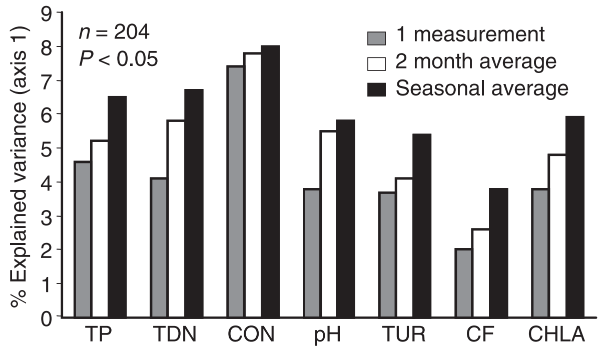


**Fig. 8** Variance explained (%) in diatom community structure of 204 samples by each environmental variable (partial CCAs) using chemistry data expressed as one-time measurement (one measurement), 2-month average (two measurements) and 3-year seasonal average (six measurements).

percent variance in species data explained by each environmental variable is higher for the seasonal average than for the other two metrics (Fig. 8). Note that each environmental variable explained a significant portion ($P \leq 0.05$) of the variance in diatom community structure whatever the metric used. In addition, a series of regressions were conducted to test the relationship between the IDEC and TP and TDN. The results showed a higher regression coefficient when the data were expressed as seasonal averages ($R^2$ for TP versus IDEC = 0.59; $R^2$ for TDN versus IDEC = 0.56; $n = 204$, $P \leq 0.05$) compared with one-time measurements ($R^2$ for TP versus IDEC = 0.46; $R^2$ for TDN versus IDEC = 0.35; $n = 204$; $P \leq 0.05$). These results indicate that diatom communities have a better relationship with averaged chemistry characterizing environmental conditions during late summer.

## Discussion

### *Diatom community and IDEC values*

Diatom community structure showed fluctuations over time in the three rivers selected. Changes in relative abundance of some taxa were observed, as well as appearance and disappearance of some others. Both phenomena induced variations in the IDEC values. Our results suggest that the IDEC is sensitive to environmental fluctuations, without being affected by natural seasonal variations (succession) in community structure. As a result, very different community structures may yield the same IDEC values.

It is interesting to note that the IDEC did not show any significant variation when TP levels were lower than 20 μg P $L^{-1}$. The IDEC values did, however, decrease significantly with higher concentrations of TP. In the Ste. Anne River for example, IDEC values dropped from 100 to 84 when TP concentration reached 24 μg P $L^{-1}$. Despite this drop in the IDEC values, the Ste. Anne River had a high ecological status throughout the sampling season. In the Nicolet River, the IDEC values ranged from 73 to 43, with the lowest values associated with TP levels higher than 40 μg P $L^{-1}$ (46–198 μg P $L^{-1}$). These values correspond to an ecological status (IDEC) varying from good to moderate. IDEC values seem to show a significant drop, accompanied by a change in ecological status, when TP concentrations are higher than a threshold level varying between 20 and 40 μg $L^{-1}$. This threshold level is comparable to that of 30 μg P $L^{-1}$ established by the Ontario Ministry of Environment and Energy (OMOEE, 1994). This criterion aims at limiting excessive growth of algae and aquatic plants in streams and rivers. The Ministry of the Environment of Québec also respects this criterion for the protection and conservation of aquatic life. This suggests that the IDEC could be used to indicate whether or not the average nutrient concentrations respect the water quality criteria. An index value higher than 80 (high ecological status) would be an indication that average TP concentrations are lower than 30 μg P $L^{-1}$.

### *Integration of temporal variability*

The results from this study showed that, along a large TP gradient, the IDEC is strongly correlated with averaged water chemistry. The weakest correlations were observed using the one-time TP measurements. Correlation coefficients increased when TP concentrations were averaged for the weeks preceding diatom sampling. This integration period, however, varied with the river. The relationship observed in the present study between stream trophic status and integration of temporal variability in TP concentrations by diatom communities is presented in Fig. 9. In the Ste. Anne River (oligotrophic), where nutrient concentrations were low and generally stable, the input of phosphorus induced a rapid change in diatom community structure and IDEC values within the following week. The IDEC therefore indicated a variation that occurred within the preceding week. In a study conducted by Pan & Lowe (1994), algal communities dominated by *A. minutissimum*, *C. placentula*, and *Fragilaria ulna* Nitzschia (Lange-Bertalot) were primarily phosphorus-limited and responded after only 6 days of nutrient enrichment, which is comparable with the one-week interval between TP increase and IDEC value decrease found in the present study (*A. minutissimum* was also one of the dominant species found in the Ste. Anne River). Without a subsequent fluctuation, the index value returned to reference conditions within the following week, although it has been shown that recovery of a diatom community is slower than the response to a perturbation (Iserentant & Blancke, 1986).

In the Nicolet River (mesotrophic), the observed integration period was approximately 2 weeks. In the eutrophic Boyer River, diatom communities seemed to be adapted to frequent and significant fluctuations in nutrient concentrations. The IDEC therefore showed a slower response to short-term fluctuations and integrated nutrient concentrations over a period

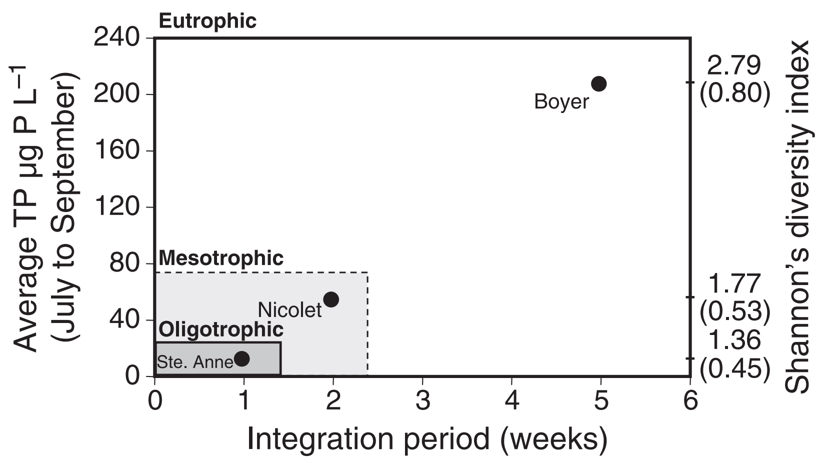


**Fig. 9** Relationship between stream trophic status and temporal variability integration in TP concentrations by diatom communities (considering a 1-week time lag for the Ste. Anne and Boyer rivers and no time lag for the Nicolet River). The diatom Shannon's diversity index (averaged for each river) is presented for the three rivers and the Shannon's equitability (evenness) is in brackets.

of 5 weeks. In order to induce a change in diatom community structure and IDEC value, an important and prolonged change in TP concentration is required. In the Boyer River, the significant peaks in TP observed during May and June 1999 induced an increase in the relative abundance of *N. palea* and *C. meneghiniana*, resulting in a 10 point decrease in the already low IDEC values. High but more stable TP concentrations observed in July promoted the growth of *N. capitatoradiata*, and resulted in the highest IDEC values for the Boyer River (27–28). Higher TP concentrations were observed again at the end of July and in August, which were accompanied by >10 point decrease in IDEC value. Similar results were observed in an impacted river of South Africa by Taylor, Janse van Vuuren & Pieterse (2007) where the tested diatom-based indices best correlated with average chemical data for a 1-month period, starting 6 weeks prior to diatom sampling. Some authors conducted field experiments by transferring biofilms from unpolluted to polluted sites, and vice-versa, to study the time needed for the community to adapt to new water quality conditions (Iserentant & Blancke, 1986; Ivorra *et al.*, 1999; Tolcach & Gómez, 2002; Rimet *et al.*, 2005). Although the methods used in these experiments differ from the present study, the results presented show that diatom communities originating from polluted streams have a longer response time than diatom communities from unpolluted stream. This general trend is comparable to what was observed in our study.

Based on these results, we propose a relationship between stream nutrient enrichment and stability of diatom-based index values as illustrated in Fig. 9. We may predict that oligotrophic streams are more sensitive to nutrient variations and that their diatom communities are directly altered by nutrient increase, while diatom communities of eutrophic rivers are less sensitive to nutrient fluctuations and major variations take a longer time to be integrated into index values. In other words, the results from this study suggest that the integration period varies as a function of trophic status and nutrient concentration variability in the streams.

Although the reasons for the observed variation in response time are not clear some hypotheses may be suggested. First, it appears that the different integration time observed as a function of trophic status is not exclusively related to the sensitivity and tolerance of the taxa (resistance to a change in the environment) because the communities from each of the three streams were composed of taxa exhibiting a wide range of autecological values. Second, it seems that the longer response time observed in the mesotrophic and eutrophic environments can not be attributed to a colonization process. Our data showed that most of the dominant taxa composing the community at each of the three sites were present during the whole sampling period, with varying abundances. A colonization process did not seem, therefore, present. However, we observed that the eutrophic Boyer River was dominated by about 20 taxa, the mesotrophic Nicolet River was dominated by about 10 taxa and the oligotrophic Ste. Anne River was dominated by only five taxa. Analyses of the entire diatom communities for each of the three rivers revealed that the Shannon's diversity index and equitability (evenness) increase as a function of trophic status (Fig. 9). This result suggests that the complexity of the community influences the time needed for restructuring the taxa. For example, in a community dominated by numerous taxa, there are no drastic changes in the community structure following a variation in environmental conditions because many taxa will respond to the changes to a different extent. However, in a community dominated by only a few taxa, a change in the abundance of a taxon will rapidly influence the community structure. Diversity–stability relationships have been the subject of numerous theoretical and empirical studies in ecology (e.g. MacArthur, 1955; May, 1973; Steiner *et al.*, 2006). Although the present study was not intended to evaluate diversity–stability processes, and although an increase in nutrient level might not represent a true perturbation (for primary producers), our results agree with previous studies on community resistance and resilience where population and community diversity influence the temporal stability (e.g. McCann, 2000; Cottingham, Brown & Lennon, 2001). The relationship presented in Fig. 9 suggests that more diverse diatom communities are more stable and more resistant to nutrient variations in the environment. The response time seems, therefore, attributed to the sensitivity (resistance) of the taxa to fluctuations in nutrients and to the complexity of the community (resilience).

Partial CCAs conducted on the low frequency data set showed that a higher percent variance in diatom community structure is explained when the water chemistry is averaged over six measurements (3-year seasonal average) rather than when one-time measurements are used. The regressions between IDEC values for the 204 sites and TP and TDN concentrations also showed better relationships when the seasonal averages were used. The stronger relationship between the IDEC and the seasonal average obtained from the low frequency data set may sound contradictory to the results obtained with the high and intermediate frequency data sets, which indicate a better fit between IDEC values and chemistry data averaged over a period of a few weeks. Actually, there is no contradiction: in all cases, diatoms and IDEC values have weak relationships with one-time chemistry measurements and the relationships improve as soon as averages are used.

Cattaneo & Prairie (1995) suggested that about eight samples are necessary to reliably estimate stream chemistry in a Canadian stream over the period of a season. In a similar study of temporal variability of northeastern United States streams, Chételat & Pick (2001) concluded that most water-column characteristics examined required sampling more frequent than monthly. The results of our study show that diatom communities (IDEC values) do not vary drastically throughout the sampling period compared with TP levels, which varied drastically in the Boyer and Nicolet rivers (up to 100-folds). In the case of the Nicolet River, the trophic status evaluated based on TP concentrations varied markedly, indicating oligotrophic to eutrophic conditions, while the IDEC values were more stable and indicated moderate to good water quality rather than covering the whole range of IDEC values. These results illustrate the integration potential of diatom-based indices. Note that the integration time of diatom-based values observed for Nicolet and Boyer rivers corresponds to TP concentrations averaged over 3–16 measurements (depending on the data sets), which are in good agreement with the conclusions in Cattaneo & Prairie (1995) and Chételat & Pick (2001).

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