Hydrobiologia **302:** 179–188, 1995.

Comparative performance of benthic diatom indices used to assess river water quality

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Received 20 February 1994; in revised form 24 March 1994; accepted 28 April 1994

Key words: river, diatom, index, nitrogen, phosphorus

Abstract

The performance of five types of benthic diatom index (four quantitative methods and a zoning system) to evaluate water quality was tested in rivers in England and Scotland. Significant correlations were observed between the four quantitative indices examined. In the case of SPI (Specific Pollution sensitivity Index) and GDI (Generic Diatom Index), over 80% of the variation in GDI was explained by a bivariate regression on SPI. Samples taken from six sites at four different times of year showed no significant influence of season on any of the indices. The zoning system led to a similar assessment of organic pollution as the SPI and GDI indices, but it was sometimes difficult to determine the zone. This method showed no obvious advantages over the quantitative indices. The high correlation between values for indices based on species and those on genera suggests that for routine monitoring, recognition to the generic level is adequate.

Introduction

Routine biological monitoring of all but the deepest rivers is based largely on macroinvertebrates (Metcalfe, 1989; De Pauw & Hawkes, 1993). Although many methods have been developed using other organisms, such as benthic algae (Whitton *et al.*, 1991), most water management organizations give these only a minor role in monitoring. Approaches using macroinvertebrates were developed originally to assess organic pollution, but modifications exist to assess other types of pollutant. More stringent legislation (European Community, 1991) and the need to monitor a wider range of substances means that the practical value of using other types of organism for monitoring should be reconsidered. The use of photosynthetic organisms to monitor eutrophication is one such case.

There is a relatively long history of the use of diatoms for biological monitoring (Whitton & Kelly, 1995) and a number of systems exist (e.g. Descy, 1979; Lange-Bertalot, 1979) to interpret data. Several of these are based on the same equation (Zelinka & Marvan, 1961) and, consequently, correlations between the various indices are generally high (Coste *et al.*, 1991). One or more of these indices has been used as an aid to routine monitoring and in canalized rivers of N-E. France they are used in preference to macroinvertebrates (Prygiel, 1991). The failure to adopt diatom-based indices more widely is due not only to the inertia encountered in adapting skills to another group of organisms, but also to other problems mentioned below.

One difficulty in the use of diatoms is the relatively large number of taxa involved. However, an index based on genera (Rumeau & Coste, 1988) performed well when compared to indices based on species (Coste *et al.*, 1991); this reduced the number of taxa involved from 200+ to 44. Prygiel (in press) concluded from a study in N-E. France that the best approach is to work at the generia level with occasional determinations to species. Another approach is to restrict identification to the most abundant species (Round, 1991), as exemplified by a system for monitoring rivers in the U.K. using about 20 key species (Round, 1993).

Another difficulty is that most of the techniques developed so far have been designed primarily to monitor organic pollution. However, there is growing interest in the use of diatoms to monitor the effects of inorganic nutrients in rivers. A trophic diatom index has been developed for use in Germany (Schiefele & Kohmann, 1993), but there are no reports of its use elsewhere.

The aim of the present study was to compare the use of four recent diatom indices based on the equation of Zelinka and Marvan (1961) plus the zoning system of Round (1993) and, in particular, to assess their value for monitoring inorganic nutrients. The indices tested were the 'indice de polluosensibilité' (= Specific Pollution sensitivity Index, SPI, Coste in CEMAGREF, 1982) and the Generic Diatom Index (GDI, Rumeau & Coste, 1988) both of which were developed as indices of organic pollution, together with the trophic diatom index (TDI) of Schiefele & Kohmann (1993) for inorganic nutrient concentrations. This has two versions: one which reflects phosphorus concentrations (TDI-P) and one which reflects phosphorus plus nitrogen concentrations (TDI-NP). It was planned to take samples from a wide range of sites and at various seasons, because it is known that invertebrate scores can be influenced markedly not only by water quality, but also by other environmental features (Armitage *et al.*, 1983).

Recently a series of papers have been published (Prygiel & Coste, 1993a, b; Prygiel, in press) concerning the use of six diatom indices to assess water quality in semi-canalized rivers in N-E. France. Two of the indices (SPI, GDI) are the name as those used in our study. A comparison of the French and U.K. studies is given in the Discussion.

Methods

Environmental measurements

Conductivity and pH were measured *in situ* using WTW meters. Water was collected in a 2-l polypropylene beaker, allowed to settle for 5 min and decanted into acid-washed bottles for transfer to the laboratory. The following analytical methods were used: Ca, atomic absorption spectrophotometry; (Whatman GF/F) filtrable reactive phosphorus (FRP) (Eisenreich *et al.*, 1975); 5-day BOD (Standing Committee of Analysts, 1989); NH_4-N, indophenol blue method (Standing Committee of Analysts, 1982a), NO_2-N by reaction with sulphanilamide and N-1-naphtholethylenediamine dihydrochloride and NO_3-N by copper hydrazine reduction followed by analysis as for NO_2-N (Standing Committee of Analysts, 1982b). Total inorganic N is the sum of the three fractions. Mean daily flow was obtained from the National Rivers Authority (NRA).

Sample collection

Five different boulders at any particular site (Round, 1993) were sampled from different positions within a defined 10-m reach, as far as possible using riffles. As far as possible, boulders (>256 mm) free of filamentous algae and obvious siltation were selected. However, at lowland sites this was not always possible, but material was removed from parts of the boulder relatively free of such contaminants. The boulders were washed briefly in stream water at the site to remove lightly attached organisms and the remaining diatoms on the boulders then removed to provide a composite sample. We have used a similar washing technique to Prygiel & Coste (1993a, 1993b), but a much less vigorous one than Round (1993). The diatoms were sampled by scraping the upper surface of the boulder with a stiff toothbrush and collecting the epilithon, suspended in stream water, in a 250-ml sample bottle. This was transferred to the laboratory in an icebox. At a few sites where there were no boulders, samples were collected from dead wood.

The effect of substratum size and flow was investigated by sampling cobbles ($>64 \leq 256$ mm) as well as boulders from two sites over a ten week period.

Preparation and identification

Samples were allowed to settle for 24 h and the supernatant decanted. Samples were first examined live and then carbonates were removed using dilute HCl. The sample was then oxidized in a mixture of concentrated sulphuric acid, potassium permanganate and oxalic acid. Clean frustules were then mounted in Naphrax (Northern Biological Supplies, Ipswich).

Diatoms were identified using an oil-immersion lens at 1000 × magnification. The nomenclature follows Krammer and Lange-Bertalot (1986–91) with the following exceptions: *Synedra* and *Hannaea* (*Ceratoneis*) are retained rather than merged into *Fragilaria*; *Cymbella sinuata* is replaced by *Reimeria sinuata* (Kociolek & Stoermer, 1987). At least 200 frustules (200–250) were identified for each sample.

Table 1. Water quality zones based on epilithic diatoms, proposed by Round (1993). Zone definitions are given verbatim. Note that some workers treat *Achnanthes microcephala* as a form of *A. minutissima*. Zone 3 is subdivided based on a downstream zonation of dominant organisms.

Zone	Description	Dominant
1	Clean water in uppermost reaches; low pH)	*Eunotia exiqua* *Achnanthes microcephala*
2	Nutrient richer and somewhat higher pH	*Hannaea arcus* *Fragilaria capucina* *Achnanthes minutissima*
3i	Nutrient rich	*Achnanthes minutissima*
ii		*Cymbella minuta*
iii		*Cocconeis placentula*
iv		*Reimeria sinuata*
v		*Amphora pediculus*
4	Eutrophic with restricted flora due to detrimental influx of materials	*Gomphonema parvulum* plus 'relative absence" of Zone 3 indicators
5	Flora grossly restricted due to detrimental influx of materials	small *Navicula* spp. (*N. atomus*, *N. pelliculosa* etc.) small *Nitzschia* spp. (*N. palea* etc) *Amphora veneta* *Gomphonema augur* *Gomphonema parvulum* *Navicula accomoda* *Navicula goeppertiana*

Table 2. Sites used in study of seasonal effects on indices. Conductivity and FRP are means (± SD) of four determinations; pH and BOD are ranges.

Stream	Grid Reference	Alt. (m)	Cond. (μS cm^{-1})	pH	FRP (mg l^{-1} P)	BOD (mg l^{-1} O$_2$)
Harwood Beck (gauging stat.)	NY 846310	380	204 ± 72	7.4–8.1	0.008 ± 0.003	<1.0–1.1
R. Browney (Langley Park)	NZ 222454	80	603 ± 129	7.3–7.6	0.240 ± 0.254	1.9–5.9
R. Skerne (Darlington)	NZ 284134	30	1010 ± 117	7.2–7.8	0.832 ± 0.793	1.2–2.5
R. Team (Causey Arch)	NZ 202560	140	785 ± 88	7.0–7.6	1.43 ± 1.24	1.3–6.5
R. Tees (Eggleston)	NY 996232	183	126 ± 22	7.4–8.0	0.013 ± 0.008	<1.0–1.5
R. Wear (Shincliffe)	NZ 287410	30	619 ± 120	7.3–8.0	0.205 ± 0.217	1.7–2.3

Table 3. Variation in mean value of four diatom-based pollution indices between end-groups produced by TWINSPAN classification of 29 'clean' sites. SPI, specific pollution index; GDI, generic diatom index; TDI-P, trophic diatom index (P version); TDI-NP, trophic diatom index (N & P version). *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$

End-group	n	Alt.	FRP	Indices			
		(m)	(mg l^{-1} P)	SPI	GDI	TDI-P	TDI-NP
A	2	250	0.348	4.20	4.08	2.66	2.62
B	5	250	<0.005	4.72	4.77	2.39	2.46
C	4	218	0.015	4.45	4.40	2.73	2.60
D	3	78	<0.005	4.52	4.55	2.58	2.57
E	4	62	0.088	3.70	3.91	2.92	2.57
F	5	33	0.133	3.34	3.45	2.90	2.89
G	2	42	0.228	3.77	3.22	2.90	2.82
H	4	20	0.354	3.34	3.32	3.08	2.81
Analysis of variance (7/21 d.f.)				7.07***	7.65***	3.39*	5.29**

Table 4. Correlations between diatom-based (SPI, GDI, TDI-P, TDI-NP) and invertebrate-based (BMWP, ASPT) pollution indices. $n = 70$ for all correlations except those including BMWP (55) and ASPT (42). *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

	SPI	GDI	TDI-P	TDI-NP	BMWP	ASPT
SPI	1					
GDI	0.91***	1				
TDI-P	−0.77***	−0.81***	1			
TDI-NP	−0.76***	−0.80***	0.82***	1		
BMWP	0.32*	0.30*	−0.28*	−0.33*	1	
ASPT	0.69***	0.69***	−0.66***	−0.65***	0.75***	1

Table 5. Effect of substratum size on the mean values (± SD) of four indices measured at two sites between May and July 1993. Difference is assessed by means of a paired sample t-test. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

	SPI	GDI	TDI-P	TDI-NP
Harwood Beck (n = 7)				
boulders	4.04 ± 0.28	3.97 ± 0.21	2.81 ± 0.10	2.75 ± 0.06
cobbles	4.02 ± 0.42	3.94 ± 0.19	2.83 ± 0.10	2.76 ± 0.06
paired t	5.7***	8.0***	6.0***	8.0***
R. Browney (n = 9)				
boulders	3.74 ± 0.10	3.49 ± 0.13	3.05 ± 0.09	2.89 ± 0.05
cobbles	3.74 ± 0.09	3.48 ± 0.14	3.06 ± 0.09	2.89 ± 0.05
paired t	0.40	0.14	0.12	0.93

Table 6. Correlations between diatom-based pollution indices and major environmental variables. Analyses are based on sites where the variable in question is greater than detection limit. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

	n	SPI	GDI	TDI-P	TDI-NP
Log FRP	61	−0.76***	−0.83***	0.77***	0.71***
Log TIN	49	−0.65***	−0.74***	0.55***	0.63***
Log BOD	55	−0.31*	−0.33*	0.32*	0.23
Log altitude	66	0.63***	0.68***	−0.75***	−0.58***
Log Ca	66	−0.43***	−0.56***	0.30*	0.42***

Description of indices and classification systems

The four quantitative indices are based on the weighted average equation of Zelinka and Marvan (1961) and have the basic form

$$\text{index} = \frac{\sum_{j=1}^{n} a_j s_j v_j}{\sum_{j=1}^{n} a_j v_j},$$

where a_j = abundance (proportion) of species j in sample, v_j = indicator value and s_j = pollution sensitivity of species j. The performance of the indices depends on the values given to the constants s and v for each taxon and the values of the indices based upon this equation range from 1 to an upper limit equal to the highest value of s. For SPI and GDI, the maximum value (5) indicates clean water; for TDI-P and TDI-NP, the maximum value (4) indicates eutrophic water. SPI is the most comprehensive index, with values of s and v available for over 1300 species (Coste, 1990), whereas GDI is based on only 44 genera (Rumeau & Coste, 1988). TDI-P and TDI-NP are each based on 105 species (Schiefele & Kohmann, 1993).

Round's (1993) approach is based on river zones rather than indices. Five zones were recognized for British rivers based on the occurrence of about 20 key indicator species. As it may be difficult to consult this booklet outside of the UK, we present our own summary of these zones in Table 1. A site is assigned to a zone on the basis of an ecological judgement made by the scientist.

Most of the taxa were included in the four indices. However, many of these are omitted by Round (1993), not being treated by him as 'true' epilithon and are excluded from his list of taxa (Table 1). At sites dominated by motile taxa such as *Navicula*, assessment based on Round's zones was therefore based on a smaller sample size.

Table 7. Effect of seasonal changes on diatom indices. Mean (± SD) of four samples (summer, autumn, winter, spring) at each of six sites is presented, along with results of two-way analysis of variance. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

Site	SPI	GDI
Harwood Beck	4.86 ± 0.09	4.62 ± 0.15
R. Browney	4.66 ± 0.18	4.46 ± 0.21
R. Skerne	3.04 ± 0.41	3.01 ± 0.65
R. Team	2.83 ± 0.42	3.24 ± 0.33
R. Tees	2.09 ± 0.07	2.25 ± 0.17
R. Wear	3.72 ± 0.32	3.48 ± 0.10
F (between sites)	55.85***	31.97***
F (between seasons)	0.79	1.23

Table 8. Relationship between TWINSPAN end-group and classification according to Round (1993). Round's zone 3 is subdivided into 5 subzones dominated, respectively, by *Achnanthes minutissima*, *Cymbella minuta*, *Cocconeis Placentula*, *Reimeria sinuata* and *Amphora pediculus*.

Round's	TWINSPAN end-group							
zone	A	B	C	D	E	F	G	H
2	1	1	1					
3i		4	1	1		1		
3ii					2			
3iii			2	2	2			1
3iv								1
3v	1					2	2	
4						2		2
Total	2	5	4	3	4	5	2	4

Statistical methods

Preliminary classification of the 'clean' dataset was performed using two-way indicator species analysis (TWINSPAN; Hill, 1979). All environmental factors used in subsequent analyses were tested for normality and an appropriate transformation applied, where necessary. In order to test the relationship between diatom and invertebrate indices, Biological Monitoring Working Party scores (BMWP: Chesters, 1980; Armitage *et al.*, 1983) and average score per taxon (ASPT) were obtained from local NRA laboratories. As locations and times of invertebrate sampling did not coincide with this survey, only those invertebrate samples were included which had been collected less than 3 km river distance or 2 months from when the diatom samples had been taken.

Correlations are based on all records for which both variables are available. Samples below the detection limit are omitted from these calculations.

Study sites

A total of 70 reaches was sampled from 36 rivers and streams in England and Scotland. These included a wide range of river conditions and water qualities, from nutrient-poor upland streams to lowland rivers subject to considerable anthropogenic influence. This latter included organic pollution (predominantly human sewage), heavy metals, pumped minewater and runoff from agricultural land. 60% of the reaches were classified as 'Good', fitting the National Water Council class 1a or 1b (Department of the Environment and Welsh Office, 1985) by the NRA. 29 of these, sampled between May and September 1992, were used to examine how the indices performed in the absence of significant pollution.

Six sites in N-E. England were sampled on four occasions over a 12-month period in order to study possible seasonal changes in values for the indices. These were: two upland, receiving little organic pollution (Harwood Beck, R. Tees); two lowland, with mild organic pollution (R. Browney, R. Wear); two lowland, receiving both sewage and industrial discharges (R. Skerne, R. Team) (Table 2). Harwood Beck and R. Browney were also used to study the effects of substratum size and flow. These sites are approximately 50 m and 4 km respectively upstream from flow-gauging stations.

Results

Number of taxa identified

A total of 150 species, representing 30 genera, were found in the 70 samples. However, only 26 species were found in 10 or more samples, and 13 in 30 or more samples. The maximum number of records for any species was 41 for *Achnanthes minutissima*, followed by 39 for *Rhoicosphenia abbreviata.*

Variation of indices across clean sites

In order to establish the extent to which values for the four indices depend upon environmental factors other than water quality a preliminary analysis was performed using data from 29 sites described as 'Good' by NRA (see Methods). A TWINSPAN analysis of these groups indicated a gradient from upland, nutrient-poor sites to lowland, nutrient-rich sites (Table 3). The mean values of SPI and GDI (see Introduction) were greater in upland sites, whilst both versions of TDI were slightly higher at lowland sites (Table 3).

Interrelationships between indices

Significant correlations were observed between the four quantitative indices examined (Table 4). TDI-P and TDI-NP were inversely correlated with SPI and GDI. The strongest relationship was observed between SPI and GDI (Fig. 1) with over 80% of the variation in GDI explained by a simple bivariate regression on SPI. However, GDI values were often much lower than expected for SPI values between 3.5 and 4.0. Several of these sites have high relative frequencies of *Amphora pediculus*, associated with eutrophic water with relatively low levels of organic pollution. *A. pediculus* is assigned scores of 4 and 1 for *s* and *v*, respectively, in the SPI, whilst the genus *Amphora* is assigned scores of 3 and 2 in GDI as several species (e.g. *A. veneta*, *A. holsatica*) are tolerant of pollution. In this study, however, *A. pediculus* was the only member of the genus found in abundance, with the exception of *A. veneta* which was abundant at sites enriched with heavy-metals.

All four diatom-based indices were correlated strongly with ASPT and, to a lesser extent, BMWP (Table 4).

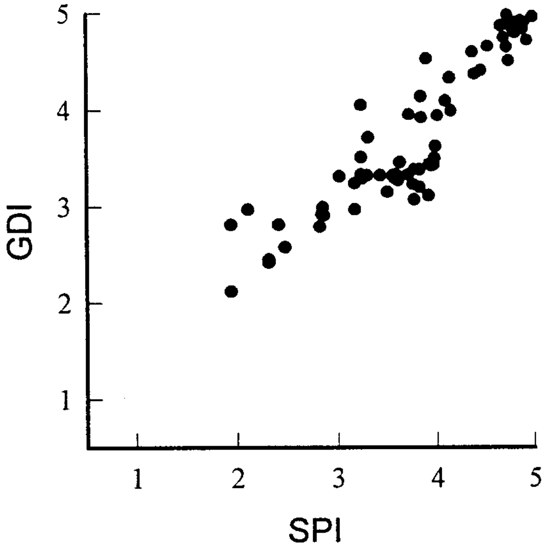

Fig. 1. Relationship between SPI and GDI. Regression equation: GDI = 0.939SPI + 0.259, $F = 341.3$, $p < 0.0001$, $r^2 = 0.832$.

Relationships between indices and environmental factors

Values of all four indices were significantly different on boulders than cobbles at the upland site, Harwood Beck, but not at the lowland site, R. Browney (Table 5). In general, the flora at Harwood Beck tended to be dominated by *Achnanthes minutissima*; however, cobbles tended to have slightly higher concentrations of motile taxa such as *Navicula*. In the R. Browney, the relative proportions of attached taxa such as *A. minutissima* and *Cocconeis placentula* and motile taxa (primarily *Navicula* spp.) were more equal and there were no obvious floristic differences between boulders and cobbles. During the course of this study there was one major spate at both sites, along with two smaller spates at Harwood Beck. Although these affected the composition of the diatom community (typically by increasing the relative proportions of attached taxa relative to motile ones), there was no obvious effect on the values of the indices (Fig. 2).

All four indices were significantly correlated with FRP and TIN (Table 6). SPI and GDI were negatively correlated with all three variables whilst TDI-P and TDI-NP were positively correlated. The greatest correlation was observed between FRP and GDI. Although TDI-P was highly correlated with log FRP, the slope of the relationship and the regression coefficient were both quite low (Fig. 3) and consequently the predictive ability of the equation is not very high. Sites with FRP concentrations below the detection limit (0.001 mg l^{-1}) were omitted from the calculation, but indicate a wide spread of TDI-P values suggesting that at least some were subject at times to much higher P concentrations. Two sites in particular appear anomalous in Fig. 3. At one of these, R. Deerness, other components of the flora (e.g. *Cladophora glomerata*, *Enteromorpha flexuosa*) indicated that the water is more usually eutrophic. The other, Cong Burn, had much of the substratum covered in silt, a factor likely to favour *Nitzschia acicularis*, which dominated the diatom flora.

The zinc-enriched sites were all in upland areas in the Northern Pennines. Dominant taxa included *Achnanthes minutissima* (typically >90%), *Fragilaria capucina*, *Meridion circulare* and *Surirella brebissonii*, all of which were also common at other upland sites and which resulted in high values for SPI and GDI. For example, Caplecleugh Low Level (10.6 mg l^{-1} Zn) had a SPI value of 4.66, whilst the R. West Allen at Coalcleugh (3.4 mg l^{-1} Zn) had a SPI value of 4.90. This indicates that these indices may be relatively insensitive to high concentrations of zinc.

Seasonal changes in values for indices

In order to assess the effect of seasonal factors on diatom indices, samples were taken at six contrasting sites (Table 2) four times between July 1992 and April 1993. SPI and GDI gave high differentiation between sites with the upland sites in particular giving scores that were very stable across seasons (Table 7). For both indices, analysis of variance indicated significant differences between sites, but not between seasons.

Assessment of Round's (1993) methodology

No sites corresponded to Round's (1993) zone 1 (see Methods) and the distinction between zone 2 and the uppermost part of zone 3 presented was unclear. As *Hannaea arcus* and *Fragilaria capucina* were never more frequent than 2.7% and 9.8%, respectively, zones were sometimes indistinct. Similarly, the distinction between zones 3 and 4 was also often blurred. Lowland sites often had high frequencies of *Gomphonema parvulum* coexisting with taxa such as *Cocconeis placentula* and *Cymbella minuta*. There was a tendency for zones to increase from left to right along the TWINSPAN classification (Table 8) and zones 1 to 3v appear to form an obvious linear sequence. Howev-

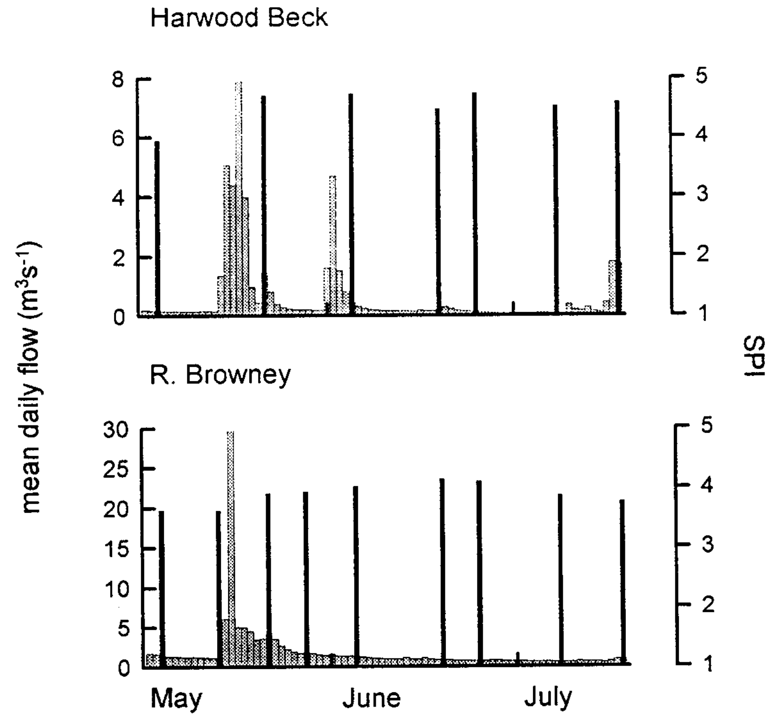

Fig. 2. Effect of flow conditions (shaded bars) on value of SPI (solid bars) at Harwood Beck and R. Browney.

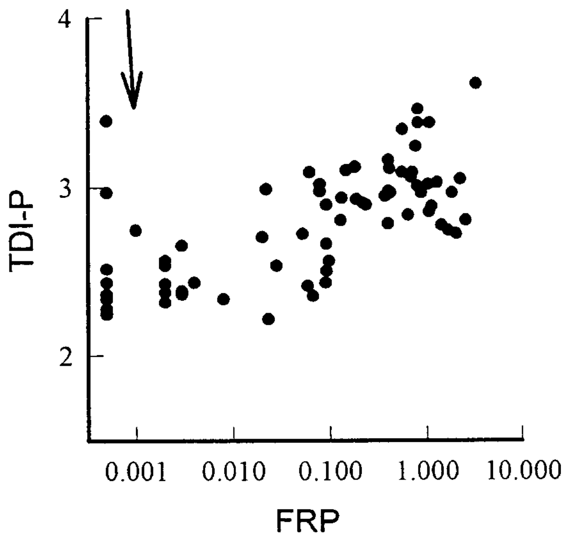

Fig. 3. Relationship between TDI-P and FRP. Regression equation (based on sites $\geq$0.001 mg l^{-1} FRP): TDI-P = 2.16 log FRP − 7.04, $n = 62$; $F = 54.07$, $p < 0.0001$; $r^2 = 0.48$.

er, four sites regarded as 'Good' by the NRA were classified in zone 4.

Discussion

The four quantitative indices gave broadly similar results, with GDI (Rumeau & Coste, 1988) showing (Table 6) a slightly higher correlation with ambient phosphate than TDI-P (Schiefele & Kohmann, 1993), in spite of the fact that the former was designed as a monitor of water quality in the broad sense and the latter specifically to monitor P. The correlation with phosphate was in all cases much higher than with BOD. Prygiel & Coste (1993b), in a study of slow-flowing waters in N-E. France, found that SPI and GDI were among indices which correlated with organic pollution, ionic strength and eutrophication, whereas two other indices correlated only with parameters related to organic pollution. Our study found a higher correlation between SPI and GDI than Prygiel & Coste (1993b) (0.91 *versus* 0.75), adding support to their suggestion that GDI provides a realistic estimate of water quality without the need for the thorough knowledge of diatom taxonomy required to use SPI. However the response of the index to a range of pollutants, such as herbicides and other complex organics, still needs to be tested.

Significant correlations were observed between the diatom indices examined in this study and BMWP and ASPT, which are used routinely for water quality monitoring in the U.K. (Table 4). In contrast, Prygiel (in press) found relatively low correlations between diatom indices (including SPI and GDI) and two invertebrate indices commonly used in France (indice biotique, indice biologique global) although stronger relationships were demonstrated by Lafont *et al.* (1988). In all these studies, however, it is difficult to separate causal factors, particularly as nutrient concentrations are often themselves correlated with variables such as BOD, associated with organic pollution. It may be difficult to identify eutrophication in the absence of organic pollution using only invertebrate indices.

The lack of any detectable influence of season suggests that diatom-based methods are equally applicable throughout the year, though some caution is needed because Prygiel & Coste (1993b) found a much lower correlation between the indices tested in July than in other months. In our study (Table 5) consistently higher values were recorded for all indices on boulders than cobbles, although the difference in mean values was slight. Major flow events, which move all but the largest boulders, appear to have had relatively little effect on the indices (Fig. 3). These factors together suggest that the indices are robust and that consistent results can be obtained throughout the year.

In many of the rivers examined in this study, *Achnanthes minutissima* was dominant in upstream reaches and was replaced by *Cocconeis placentula* in the middle reaches. Although the fastest currents may be expected in the upper reaches, *C. placentula* has been shown to be more firmly attached to the substratum (Anyam, 1990). Thus it is likely that the dominance of *Achnanthes minutissima* in the upper reaches is due to a combination of factors. *Cocconeis placentula* remains abundant even in the presence of mild organic pollution and thus cannot be regarded as an indicator of 'clean' water. In the presence of mild organic pollution, *Gomphonema parvulum* and motile taxa such as *Navicula gregaria*, *N. lanceolata* and *Nitzschia palea* often co-exist with *C. placentula*. The weighting of *Cocconeis placentula* in SPI reflects this ecological tolerance; thus it should be clear that not all sites have the theoretical potential to achieve the maximum value of the index. Future development of indices should consider incorporating means of scaling results to the potential achievable at a site, as has been advocated for invertebrate-based monitoring (RIVPACS: Wright *et al.*, 1989). A simple example for diatoms was described in Whitton & Kelly (1995).

It is suggested that the future development of indices designed to monitor eutrophication should focus on sites with relatively low organic pollution. Although high concentrations of organic pollution are usually accompanied by high nutrient levels, other factors may have a marked influence on community composition. Some species (e.g. *Amphora pediculus*) tend to be abundant when nutrient levels are high, but organic pollution is relatively low, whereas others (e.g. *Nitzschia palea*) can thrive at sites with high levels of nutrients and organic pollution. *Amphora pediculus* may therefore be a better indicator of nutrients than *Nitzschia palea*. The inclusion of organic pollution-tolerant species in an index of eutrophication can lead to anomalous results, as was perhaps the cause for the high value for TDI at Cong Burn (see Results).

The vigorous washing procedure (jet of distilled water on boulders returned to laboratory) recommended by Round (1993) offers no obvious advantage to the less vigorous washing used by Prygiel & Coste (1993a, 1993b) and us. Apart from the logistic problems created by the need to transport rocks and the effect that the period of transport may have on diatom attachment, it seems irrational not to treat films of gliding diatoms, such as *Navicula*, growing on boulders as epilithon; temperate zone communities in spring are often dominated overwhelmingly by such organisms. As organic pollution is usually associated with an increased load of suspended material, it is likely that changing proportions of taxa such as *Navicula* can provide valuable information for monitoring.

The other feature of Round's (1993) system, the use of zones, also showed no obvious advantage to the use of indices. Maps showing river quality zones often play an important role in water management, but it is easy to use information from diatom indices indicates to generate suitable zones for comparison with zones based on other criteria. Further, indices provide a more objective basis for assessing temporal changes at a site.

The success of GDI in both the slow-flowing rivers of N-E. France and the faster-flowing waters characteristic of most of our study sites indicates that the GDI provides a suitable approach for routine monitoring and a basis for developing specialist indices. The assessments of various approaches by Prygiel & Coste (1993b) and in this study indicate that it would be better to concentrate on the GDI (and perhaps also SPI) and test this rigorously over a wider range of rivers. There seems little point in maintaining a range of other indices with few obvious advantages for general surveys.

The inclusion of a limited number of easily recognizable species may improve the effectiveness of GDI for monitoring particular types of pollutant. For instance, *Amphora pediculus* appears to show an atypical response to organic pollution (Fig. 1) and could well be separated from the remainder of the genus. The selection of a particular index plus various sets of key species for special purposes would also focus interest on those taxa where experimental studies on the relative importance of environmental factors would be most useful. The results of such experimental studies could lead to modifications of the main list of genera chosen for GDI and also certainly do so for the lists of species to be added for special purposes.

Acknowledgments

Part of this work was carried out under a UK National Rivers Authority fellowship to M.G.K. The views expressed in this paper are not necessarily those of the NRA.

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