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The Trophic Diatom Index: a new index for monitoring eutrophication in rivers

M. G. Kelly & B. A. Whitton*
Department of Biological Sciences, University of Durham, Durham DH1 3LE, UK
*(*Author for correspondence)*

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Abstract

A index for monitoring the trophic status of rivers based on diatom composition ('trophic diatom index', TDI) has been developed, in response to the National Rivers Authority (England & Wales)'s needs under the terms of the Urban Wastewater Treatment Directive of the European Community. The index is based on a suite of 86 taxa selected both for their indicator value and ease of identification. When tested on a dataset from 70 sites free of significant organic pollution, this index was more highly correlated with aqueous P concentrations than previous diatom indices. However, where there was heavy organic pollution, it was difficult to separate the effects of eutrophication from other effects. For this reason, the value of TDI is supplemented by an indication of the proportion of the sample that is composed of taxa tolerant to organic pollution.

The index was tested on the R. Browney, N-E. England, above and below a major sewage discharge. TDI values indicated that the effect of inorganic nutrients on the river downstream of the discharge was slight as the river was already nutrient-rich, but there was a large increase in the proportion of organic pollution-tolerant taxa. This indicates that the river was already so eutrophic upstream of the discharge that tertiary treatment to remove P would not be effective unless other aspects of the discharge were also improved.

Introduction

There is a continuing need for new and improved methods of monitoring the state of the aquatic environment. One such is for monitoring eutrophication in running waters, which, in Europe, has been brought into sharp focus by the Urban Wastewater Treatment Directive (European Community, 1991). A critical part of this legislation is the identification of 'sensitive areas' (SAs) where more stringent wastewater treatment is required to prevent or reverse eutrophication (European Community, 1991). As the capital costs of installing tertiary treatment for nutrient removal at large sewage works are high, there is an additional caveat which requires that 'removal of P should be included unless it can be demonstrated that removal will have no effect on the level of eutrophication' (European Community, 1991).

As a result of this legislation, there is an urgent need to develop a broad range of standard techniques to monitor eutrophication (Kelly & Whitton, 1995) in order to prepare cases depending upon individual circumstances. Some techniques (e.g. macrophyte surveys) are already in use, whilst others require more development to meet specific monitoring requirements. The use of diatoms falls into this latter category.

Several diatom-based indices have been developed (Whitton & Kelly, 1995), some of which are used routinely by water management bodies (Prygiel & Coste, 1993). Most are based on the weighted average equation of Zelinka and Marvan (1961) and are general pollution indices. Although a principal components analysis of data collected from the Artois-Picardie region of France indicated a correlation between some diatom indices and eutrophication, the relationship between

Table 1. Distribution of sample sites used to develop trophic diatom index.

Catchment	Number of sites	Notes
Axe (S-W. England)	3	R. Axe (2) & R. Yarty
Coquet (N-E. England)	4	R. Coquet & tributaries
Water of Fleet (S-W. Scotland)	1	
Humber (N-E. England)	2	Both R. Swale
Otter (S-W. England)	2	
Severn (Central England)	10	R. Avon & tributaries
Tees (N-E. England)	5	R. Tees (3) & R. Skerne (2)
Thames (S-E. England)	12	R. Kennet & tributaries
Tweed (S-E Scotland)	4	R. Tweed & tributaries
Tyne (N-E. England)	6	Mainly upland tributaries
Urr (S-W. Scotland)	1	
Wear (N-E. England)	16	R. Wear (8) and tributaries
Wellend (E. England)	3	R. Wellend, R. Gwash, R. Chater
Witham (E. England)	1	

Table 2. Descriptive statistics for key environmental variables for 70 "clean" sites. TON, total oxidised nitrogen (nitrate + nitrite); FRP, filtrable reactive P. n = 70.

Variable	Unit	Detection limit (d.l.)	No. below d.l.	Min.	Max.	Median
Slope	$m\ km^{-1}$			0.3	76	2.5
Altitude	m			9	530	80
pH				5.6	8.8	7.6
Conductivity	$\mu S\ cm^{-1}$	10	0	74	1267	545
Total alkalinity	$meq\ L^{-1}$	0.5	0	0.5	125	9.0
TON	$mg\ L^{-1}$	0.10	10	<0.10	15.91	2.30
NH_4-N	$mg\ L^{-1}$	0.05		<0.05	0.41	0.05
FRP	$mg\ L^{-1}$	0.001	6	<0.001	2.035	0.079

these same indices and variables associated with organic pollution was much stronger (Prygiel & Coste, 1993). For this reason, a purpose-designed index to monitor eutrophication in rivers seems more appropriate. However, the development of such indices presupposes that the response of benthic diatoms to nutrients in the absence of organic pollution can be separated from their response to organic pollution.

In Germany the saprobic zoning system of Lange-Bertalot (1979) was adapted to include the effects of inorganic nutrients in the absence of significant organic pollution (Steinberg & Schiefele, 1988) and subsequently this has been developed into two quantitative indices (to monitor P and N + P, respectively) by Schiefele and Kohmann (1993). However, although there was a significant relationship between these trophic indices and P when tested on UK sites, the slope was low and the values computed for sites with P (as filtrable reactive phosphorus, FRP) from <0.001 to >3.5 mg L^{-1} all fell in the range 2.0–3.3 (Kelly *et al.*, 1995). Correlations between these indices and P were of the same order as those between two French indices (indice de polluosensibilité ≡ specific pollution index, SPI (Coste in CEMAGREF, 1982), and indice diatomique generique ≡ generic diatom index, GDI) and P and, in fact, the best correlation was observed between P and GDI, an index based on 44 diatom genera (Rumeau & Coste, 1988). This was designed as

Table 3. Spearman's Rank Correlations between key environmental variables examined during study. Cond., conductivity; alk., total alkalinity; TON, total oxidised nitrogen; FRP, filtrable reactive P. A threshold confidence limit of $p = 0.01$ is used to protect against 'type 1' errors. **, $p < 0.01$; ***, $p < 0.001$. $n = 70$.

	Slope	Altitude	pH	Cond.	Alk.	TON	NH_4-N	FRP
Slope	1.000							
Altitude	0.774 ***	1.000						
pH	−0.199	−0.268	1.000					
Cond.	−0.634 ***	−0.495 ***	0.127	1.000				
Alk.	−0.508 ***	−0.365 **	0.288	0.669 ***	1.000			
TON	−0.690 ***	−0.590 ***	0.237	0.764 ***	0.721 ***	1.000		
NH_4-N	−0.366 ***	−0.271	−0.155	0.126	−0.064	0.200	1.000	
FRP	−0.686 ***	−0.644 ***	0.103	0.754 ***	0.483 ***	0.765 ***	0.326 **	1.000

a general pollution index and, consequently, it is difficult to separate direct autecological responses to P from responses to other variables correlated with P in a dataset that includes a wide variety of river types and water qualities.

The objective of this study was to develop a practical index for monitoring trophic status in UK rivers. As trophic variables are often highly correlated, it is better to model a broad response to 'nutrients' or 'eutrophication' using a single variable (e.g. molybdate-reactive P ≡ FRP ≅ 'orthophosphate') as a proxy. Although diatoms have been used in studies concerned with water management before (most notably, acidification studies, Batterbee, 1984), practical work was largely the provenence of academic scientists. By contrast, monitoring river eutrophication is likely to be performed largely by biologists employed in the water industry, so it would be helpful to have a technique that is robust and can be learnt rapidly. The Biological Monitoring Working Party (BMWP) score, used routinely in the U.K for assessment of organic pollution using macroinvertebrates (Chesters, 1980; Armitage *et al.*, 1983), was used as a benchmark for the development of a trophic diatom index (TDI). The BMWP score involves identification of less than 100 taxa (mostly families) and practitioners quote a 'learning curve' for the technique of about three months.

Materials and methods

Study sites and environmental measurements

In order to assess the influence of nutrients on diatom community composition, 70 sites considered to be 'clean' by the National Rivers Authority (NRA) in England or, in Scotland, by the appropriate River Purification Board, were selected (Table 1). This was defined as chemical class 1A or 1B (National Rivers Authority, 1991), except where biological quality overrode this. Good biological quality was defined as values >0.9 for the Ecological Quality Index (based on River Invertebrate Prediction and Classification System, RIVPACS, simulations, Wright *et al.*, 1989) and borderline cases were discussed with local biology staff before inclusion. In addition, ten sites subject to organic pollution (chemical class 2–3) were examined to test the performance of the index in these waters. Samples collected in an earlier study (Kelly & Whitton, 1994) were also examined to provide a broader picture of diatom distribution in relation to nutrient concentrations.

A single sample (water + diatom) per site, collected under low flow conditions between April and September 1992-4, was included in the dataset. P (as FRP) was analyzed at NRA laboratories (using methodology of Standing Committee of Analysts, 1981), with

Table 4. Taxon sensitivities (s) and indicator values (v) for trophic (P) diatom index.

Taxon	s	v	Comment
Achnanthes lanceolata (Bréb.) Grun. in Grun. & Cleve	5	2	Includes *A. rostrata* Østr.
Achnanthes minutissima Kütz.	2	2	Includes *A. microcephala* (Kütz.) Grun.
Achnanthes - other	3	1	
Amphipleura Kütz.	1	3	
Amphora pediculus (Kütz.) Grun. *ex.* A. Schmidt	5	2	
Amphora - other	5	1	
Anomoeoneis Pfitzer	1	2	
Asterionella Hassall	3	1	
Attheya West	4	1	
Aulacosira Thwaites	2	1	
Brachysira Kütz.	1	3	
Caloneis Cleve	3	1	
Ceratoneis arcus			See *Hannaea*
Cocconeis pediculus Ehr.	4	2	
Cocconeis placentula Ehr.	3	2	
Cocconeis - other	2	2	
Ctenophora pulchella (Grun.) Williams & Round	2	1	Formerly *Synedra pulchella*
Cyclostephanos Round	5	1	
Cyclotella Kütz. ex. Bréb.	5	1	
Cymatopleura Smith	4	1	
Cymbella affinis Kütz.	1	3	
Cymbella delicatula Kütz.	1	3	
Cymbella microcephala Grun.	1	2	
Cymbella minuta Hilse *ex.* Rabh.	3	2	Includes *C. silesiaca* Bleisch
Cymbella sinuata			See *Reimeria sinuata*
Cymbella - large forms	4	2	Nominally > 50μm. Includes *C. caespitosa* (Kütz.) Brun. *C. lanceolata* (Ehr.) Kirchner
Cymbella - others	2	1	
Denticula Kütz.	2	2	
Diatoma tenuis Ag.	3	2	
Diatoma vulgare Bory	5	3	

Continued overleaf

the exception of sites likely to have low concentrations (<0.03 mg L^{-1} P), which were analyzed in Durham using Eisenreich *et al.* (1975)'s modification of the molybdate blue method.

In addition, a case study was performed on the R. Browney (Co. Durham, U.K.) above and below a major sewage treatment works (STW, serving population of 14 900 + 400 m^3 d^{-1} trade effluent). Water chemistry and diatom samples were collected between July and November 1994. Above the works (NZ 258389), FRP concentrations ranged from 0.02–1.28 mg L^{-1} P, whereas downstream (NZ 267382) the range was 0.99–2.44 mg L^{-1} P. There were also significant increases in BOD and ammonium-N and the water quality dropped from class 1b to class 2. The highest values were observed during a 4-week period (4–29 October) during which pumps discharging minewater from abandoned coal mines (normally a major diluent for the sewage effluent) were switched off.

Biological methods

Epilithic diatom samples were collected following the method of Round (1993), except that samples were removed from the substrate in the field, to avoid the necessity of transporting boulders to the laboratory. In general the exposed surfaces of five boulders or cobbles from within a reach were sampled. This involved a brief rinse in the stream to remove loosely-attached

Table 4. Continued.

Taxon	s	v	Comment
Diatoma - other	2	1	
Didymosphenia geminata (Lyngb.) Schmidt	2	3	
Diploneis Ehr.	1	1	
Ellerbeckia arenaria Crawford	4	2	
Epithemia Bréb.	1	2	
Eunotia Ehr.	1	3	
Fragilaria brevistriata			See *Pseudostaurosira*
Fragilaria capucina Desm.	2	2	
Fragilaria pinnata			See *Staurosirella*
Fragilaria vaucheriae (Kütz.) Peters	3	2	
Fragilaria - other	2	1	Including *Staurosira*
Frustulia Ag.	1	2	
Gomphoneis Cleve			
Gomphonema angustatum (Kütz.) Rabh.	1	2	
Gomphonema olivaceoides Hust.	2	3	
Gomphomema olivaceum (Hornemann) Bréb.	5	2	
Gomphomema parvulum (Kütz.) Kütz.	5	3	
Gomphonema - other	3	1	
Gyrosigma Hassall	5	2	
Hannaea arcus (Ehr.) Patr	1	3	
Hantzschia Grun.	5	1	
Martyana (Hérib.) Round	5	2	Formerly freshwater species of *Opephora*.
Melosira varians Ag.	4	2	
Meridion circulare (Grev.) Ag.	2	3	
Navicula cryptotenella Lange-Bertalot + other species	5	2	Includes *N. menisculus* Schum., *N. reichardtiana* Krammer & Lange-Bertalot var. *reichardtiana* Krammer & Lange-Bertalot
Navicula gregaria Donkin	5	1	
Navicula lanceolata (Ag.) Ehr.	5	2	
Navicula tripunctata (O.F. Müll.) Bory	4	2	
Navicula - other	4	1	Excluding small species
Navicula - small species	5	1	Nominally <12 μm
Neidium Pfitzer	2	3	

Continued on p. 439

material, followed by a vigorous brush with a toothbrush (thoroughly washed between samples) to remove all obvious surface films of algae. As far as possible, boulders free of filamentous algae and obvious siltation were selected; however, at lowland sites this was not always possible, but care was taken to remove material from parts of the boulder relatively free of such contaminants. At a few sites in the upper R. Kennet the substratum was composed predominantly of flints and gravel and only a few cobbles and several cobbles were needed to be sampled to collect sufficient material. At some lower sites in the R. Kennet and R. Avon (Table 1), there were very few boulders and samples from these sites were often collected from a single boulder.

Samples were transported to the laboratory in an ice box and examined live within 48 h of collection. They were then preserved with Lugol's iodine until preparation. Carbonates were first removed using 0.1 M HCl. Several methods for the preparation of diatoms exist, such as that of Barber and Haworth (1978). We used a slightly different mixture from theirs to oxidise organic matter, with concentrated H_2SO_4 (5 ml), $KMnO_4$ (0.1 g) and saturated oxalic acid (10 mL) (based on information from the late J. R. Carter) until they were digested. Clean valves were mounted in Naphrax prior to identification. Counts of at least 200 valves were

Table 4. Continued.

Taxon	s	v	Comment
Nitzschia acicularis (Kütz.) Smith	3	1	
Nitzschia amphibia Grun.	4	3	
Nitzschia dissipata (Kütz.) Grun.	4	2	
Nitzschia pusilla Grun. emend. Lange-Bertalot	4	2	
Nitzschia sigmoidea (Nitz.) Smith	4	2	
Nitzschia - other	4	1	Includes *N. palea*
Opephora			See *Martyana*
Pinnularia Ehr.	1	3	
Pseudostaurosira brevistriata (Grun.) Williams & Round	2	2	
Reimeria sinuata (Greg.) Kociolek & Stoermer	4	3	
Rhizosolenia Ehr.	4	1	
Rhoicosphenia abbreviata (Ag.) Lange-Bertalot	4	1	
Rhopalodia (Müll.)	1	1	
Sellaphora Mereschkowsky			Included with small *Navicula*
Stauroneis Ehr.	5	2	
Staurosirella Williams & Round	4	1	
Stenopterobia Bréb & Van Heurck	1	1	
Stephanodiscus Ehr.	5	3	
Surirella Turp.	3	1	
Synedra pulchella			See *Ctenophora pulchella*
Synedra ulna (Nitz.) Ehr.	3	1	
Synedra - other	4	1	
Tabellaria Ehr.	2	3	
Tetracyclus Ralfs	1	1	
Thalassiosira Cleve	4	1	

Table 5. Comparison between Round's zoning system and TDI.

Zone	Characteristic species	TDI s	TDI v
1	*Eunotia exigua*	1	3
	Achnanthes microcephala (see *A. minutissima*)		
2	*Hannaea arcus*	1	3
	Fragilaria capucina	2	2
	Achnanthes minutissima	2	2
3a	*Achnanthes minutissima*	2	2
3b	*Cymbella minuta*	3	2
3c	*Cocconeis placentula*	3	2
3d	*Reimeria sinuata*	4	3
3e	*Amphora pediculus*	5	2

made using 1000 × magnification; the decision to use this total was based on several graphs (e.g. Fig. 1; see also Whitton and Kelly, 1995, Fig. 1) relating the TDI value against number of valves counted. The nomenclature of Krammer and Lange-Bertalot (1986–91) was used with a few exceptions associated mainly with their controversial treatment of the Fragilariaceae and with taxonomic revisions suggested by Round *et al.* (1990). Other taxonomic works which were consulted included Hustedt (1930), Patrick and Reimer (1966, 1975), Carter and Bailey-Watts (1981) and Barber and Haworth (1978).

Development of index

Data were stored in a Paradox database known as 'STARS' (Stream Algae Recording System: Kelly and Whitton, 1994). This is a fully relational database that can produce various types of output, ranging from the lists of taxa found at a particular site and the sites where a particular taxon is found, to information on the eco-

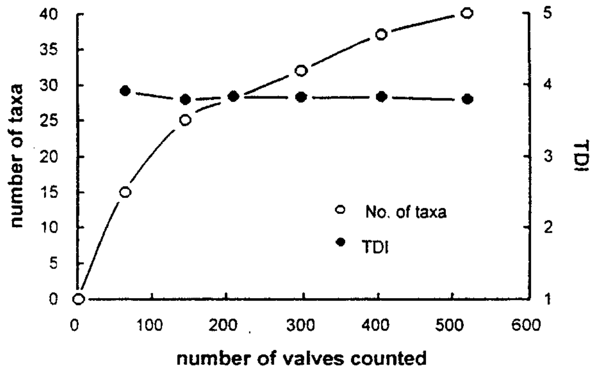

Fig. 1. Relationship between number of taxa observed and number of valves counted. Results based on survey of R. Og, a tributary of R. Kennet, southern England, 1 August 1994.

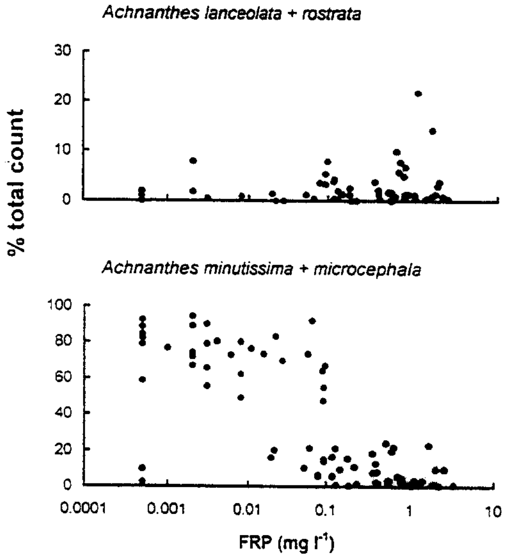

Fig. 2. Relationship between ambient P (as FRP) and percent total count represented by *Achnanthes minutissima* (including *A. microcephala* and *A. lanceolata* (including *A. rostrata*).

logical ranges of taxa. This was used generate a list of genera common in rivers, updated to include recent taxonomic revisions (Round *et al.*, 1990) which have led to the erection of several new genera, particularly amongst the araphid diatoms. A species was split from a genus if it was found in more than 10% samples and is relatively easily identified. For example, the genus *Achnanthes* is common across a wide range of conditions. Thirteen species were found during the initial phase of this project, of which only two were ever abundant: *Achnanthes minutissima* and *A. lanceolata.* None of the remainder were found at more than 5 sites or at greater than 2.5% total count. For practical purposes, therefore, the genus is treated as follows:
Achnanthes lanceolata (including *A. rostrata*);
Achnanthes minutissima (including *A. microcephala*);
Achnanthes – other species.

A. minutissima is often the dominant diatom in upland oligo/mesotrophic rivers and streams, whereas *A. lanceolata* tends to be most common in more nutrient-rich conditions (Fig. 2). Both respond to P differently and, therefore, represent good indicators of trophic status. In order to avoid taxonomic confusion, *A. rostrata* is included with *A. lanceolata* and *A. microcephala* with *A. minutissima.*

A number of other genera presented particular problems. For example, a number of large forms of *Cymbella* (including *C. caespitosa* and *C. lanceolata*) appear to be characteristic of eutrophic water, whereas most of the genus is more frequent at lower nutrient concentrations. As these large forms of *Cymbella* do not constitute a natural taxonomic group, an 'operational' category, defined by cell size is used instead. Similarly, many small forms of *Navicula* (including *Sellaphora*) were extremely abundant in highly eutrophic (usually organically-polluted) water and these too are separated from the remainder of the genus. Several of these species can exceed 12 μm in length, but this value was chosen as an arbitrary limit, to avoid inclusion of small valves of other *Navicula* species. This list of taxa reflects the sites chosen for study. No doubt surveys in other rivers would lead to further refinements. For instance, no sites subject to saline pollution were included.

The relationship between taxon and environment was established by examining graphs summarizing percent count versus FRP for each taxon. 'Sensitivity' values of between 1 and 5 were assigned to each taxon depending upon the concentration at which taxa were most abundant. The limits for each value were broadly based on OECD criteria for lakes (Newman, 1988):

1. <0.01 mg l^{-1}
2. $\geq 0.01, <0.035$ mg l^{-1}
3. $\geq 0.035, <0.1$ mg l^{-1}
4. $\geq 0.1, <0.3$ mg l^{-1}
5. ≥ 0.3 mg l^{-1}

'Indicator' values depended on the spread of values around this peak.

In cases where P concentrations based on spot samples were atypical for the site (based on previous surveys), a wider database of species composition and

Table 6. Interpretation of proportion of count composed of taxa tolerant to organic pollution (*Gomphonema parvulum, Navicula gregaria, N. lanceolata* small *Navicula* and *Sellaphora* spp., *Nitzschia* spp.).

Proportion of count	Interpretation
<20% total valves belonging to tolerant taxa	Free of significant organic pollution
21–40% total valves belonging to tolerant taxa	Some evidence of organic pollution
41–60% total valves belonging to tolerant taxa	Organic pollution likely to contribute significantly to eutrophication of site
>61% total valves belonging to tolerant taxa of flora tolerant	Site is heavily contaminated with organic pollution.

water chemistry was consulted and, where there were few records of a particular taxon, a broader search of the ecological literature was undertaken. At this stage, no attempt was made to distinguish between indicators of eutrophic conditions and indicators of organic pollution. Taxon weightings, produced by these processes are given in Table 4. Calculation of the index uses the weighted average equation of Zelinka and Marvan (1961):

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

where a_j = abundance (proportion) of species j in sample, v_j = indicator value (1–3) and i_j = pollution sensitivity (1–5) of species j. The value of TDI can range from 1 (very low nutrient concentrations) to 5 (very high nutrient concentrations). Other indices used were SPI and generic diatom index (GDI, Rumeau & Coste, 1988). Both are calculated in the same way as TDI and vary from 1 (clean water) to 5 (grossly polluted water).

Results

The 70 'clean' sites used in the development of the index covered a range of water conditions typical of U.K. with P (as FRP) ranging from <0.001 mg L^{-1} at some upland sites to >1.00 mg L^{-1} at lowland sites (Table 2). The highest concentrations were found downstream of STWs, although chemical and biological (macroinvertebrate) evidence suggested that recovery had taken place. Nutrient concentrations, together with some physico-chemical characteristics, were highly correlated (Table 3).

Table 7. Changes in diatom indices (SPI, GDI, TDI) and % count composed of taxa tolerant to organic pollution (% tolerant) above and below Browney sewage works, along with results of paired sample one-sided t-test (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

Index	Above	Below	*t*
SPI	3.78 ± 0.10	2.32 ± 0.51	7.03 ***
GDI	3.37 ± 0.12	2.74 ± 0.36	4.58 **
TDI	4.18 ± 0.18	4.63 ± 0.36	2.23 *
% tolerant	12.7 ± 6.2	69.8 ± 15.9	8.19 ***

Weightings were produced for 86 taxa, based on the criteria outlined in Materials and methods. Those for the dominant taxa in river epilithon broadly agree with the first three zones proposed by Round (1993), with a sensitivity of 1 for *Eunotia exigua*, the dominant in his 'zone 1' ('clean water in uppermost reaches'), through to 5 for *Amphora pediculus*, the dominant of the lowermost subzone of his 'zone 3' ('nutrient rich'; Table 5). Taxon weightings were used to calculate values of TDI for the dataset of 70 sites which were then plotted against ambient P concentrations. The results show a strong relationship (Fig. 3), with a correlation of $r = 0.595$. This compares to a value $r = 0.513$ for the relationship between GDI and FRP tested on the same dataset. When taxa generally considered (e.g. Coste in CEMAGREF, 1982) to be tolerant to organic pollution (*Gomphonema parvulum, Navicula gregaria, N. lanceolata*, small *Navicula* and *Sellaphora* spp., *Nitzschia* spp.) were removed from the index, results were little changed for the 70 'clean' sites. However, when a separate set of organically polluted sites was examined, values for the modified index were much lower than for the original index including all taxa (Fig. 4).

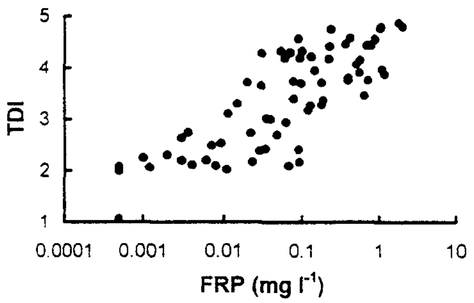

Fig. 3. Relationship between trophic diatom index (TDI) and ambient P (as FRP), tested over 70 'clean' sites. Regression equation: TDI = 4.32 + 0.75 logFRP; r^2, 0.63; F, 115.7; p<0.001.

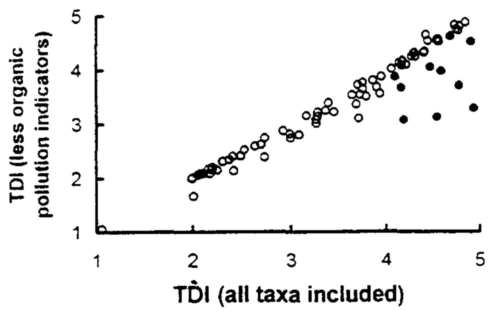

Fig. 4. Relationship between trophic diatom index with and without organic pollution indicators removed. Open circles: 'clean' sites; closed circles: subset of organically polluted sites.

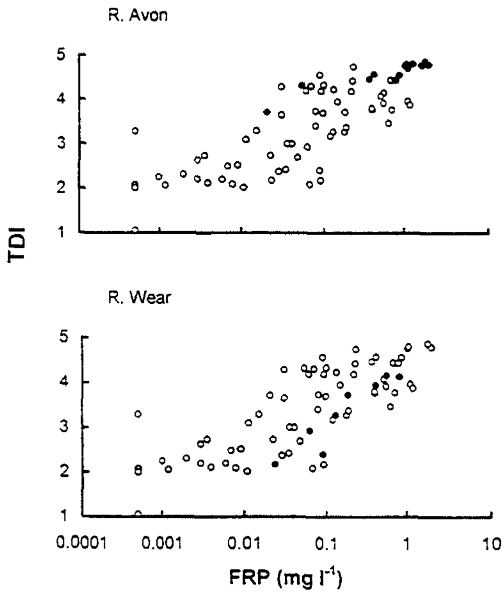

Fig. 5. Response of diatom communities in R. Avon and R. Wear to TDI.

It is clear from this that a functional index will require both a measure of eutrophication and an indication of the proportion of this eutrophication associated with organic pollution. One simple measure is the proportion of the flora that is tolerant to organic pollution (i.e. those taxa listed above: Table 6).

A detailed analysis of data indicated that part of the variation might be attributable to differences between river systems. For example, sites on R. Avon tended to have higher values of TDI for a given P concentration than sites on the R. Wear (Fig. 5). The cause of these effects is not clear at this stage: inclusion of conductivity (a correlate of hardness) as an extra variable in the regression equation had little effect on the relationship between TDI and FRP.

Use of index

The case study on the R. Browney provides an example of how the TDI can be used to assess sources of nutrients. The benthic diatom flora upstream of the sewage works discharge is typical of a river receiving mild organic pollution and with a low N:P ratio (median = 3.4). The dominant species are *Cocconeis placentula* and *Amphora pediculus*, along with other species typical of eutrophic water. Species diversity in these samples was relatively high, with typically more than 25 species per sample. The proportion of motile genera (*Navicula*, *Nitzschia*) was usually less than 15%. However, during the period when the river was not diluted with minewater (see Materials and methods), the proportion was higher (28–35%), with *Navicula tripunctata* and *Nitzschia dissipata* especially abundant, these being species tolerant of eutrophication but relatively intolerant of organic pollution.

Downstream of the discharge, the flora was dominated by organic pollution-tolerant species particularly small *Navicula* spp. (*N. atomus*, *N. saprophila*, *N. subminuscula* etc), *Gomphonema parvulum* and *Achnanthes lanceolata* and here there was relatively little change after the pumped minewater was turned off.

SPI and GDI indicated mild organic pollution above the discharge (Table 5) and there was a drop of approximately one unit below. Both water chemistry and TDI indicated that the river was eutrophic above the discharge, and the slight increase below was accompanied by a large increase in the proportion of pollution tolerant taxa in the sample, suggesting that the effect of nutrients *per se* was slight.

Discussion

Although large sewage discharges undoubtably contribute large amounts of P to rivers, high concentrations of P are common in lowland rivers without obvious signs of an organic pollution-tolerant fauna or flora. In some cases, this is due to self-purification downstream of a discharge whilst in others the P is contributed by smaller sewage works or other sources (e.g. storm sewers, agriculture). This has important implications when assessing the trophic status of rivers prior to designation as 'sensitive areas', since the effects of P enrichment need to be separated from the effects of organic pollution.

The TDI represents a useful monitoring tool for site assessments prior to designation of sensitive areas. However, diatom communities are also subject to medium and long-term changes due to factors unrelated to nutrients and, at least at first, the TDI will require careful interpretation. In general, light, temperature and nutrients together define the potential for primary production while water velocity and grazing influence the development of biomass. Differential effects of these factors on different species will, in turn, lead to changes in community composition.

It is not clear what causes the differences between rivers (Fig. 5). Studies on macroinvertebrates have shown that a variety of geographical factors can contribute to different communities (Wright *et al.*, 1984) and similar factors may operate on benthic diatom communities. Although climate may influence community structure, diatom indices are not subject to marked seasonal variation (Kelly *et al.*, 1995) permitting samples to be collected throughout the year.

Many of the streams and rivers where the TDI could be used contain significant amounts of organic pollution in addition to inorganic nutrients, and this may exert different effects on the flora than nutrients alone. Features which may affect a taxon's performance under such conditions include ability to survive in low concentrations of dissolved oxygen, avoidance of settled solids, capacity to use organic carbon sources and tolerance of high concentrations of ammonium, nitrite and other potentially toxic materials. However the ecological 'niche' of a taxon is likely to be determined by a combination of these factors along with its competitive ability in high nutrient concentrations. It is therefore easy to presume a response to nutrients *per se* in an organically-polluted river, whereas a genus such as *Nitzschia* is well adapted to extremes of other factors as well (Patrick, 1977). The situation is further complicated because *Nitzschia* spp. are common in the plankton of nutrient-rich African lakes (e.g. Talling, 1987), where these other factors are unlikely to be significant and the success of some *Nitzschia* species in eutrophic conditions has been attributed to obligate nitrogen heterotrophy (Hellebust & Lewin, 1977; Kilham *et al.*, 1986), which would overcome problems associated with low N: P ratios.

For these reasons it is important to assess not just eutrophication, but also the likely influence of organic pollution on floristic composition. A simple means of doing this is to calculate the percent of valves of taxa characteristic of organically-polluted water. This worked well for the study of the R. Browney where it demonstrated that tertiary treatment to remove P might not be effective unless it also addressed other characteristics of the effluent (BOD, suspended solids etc).

What is the likely time scale for floristic changes? This will depend on both the growth rates of individual species and the rate at which the whole community can respond. In the laboratory, generation times as short as 8 h have been recorded for the plankton species *Asterionella formosa* (Reynolds, 1984), although Lund (1964) recorded a minimum of about 15 h *in situ* during the spring bloom. There are few data for streams on generation times of individual species or changes in whole communities, but the rate of change is likely to reflect the 'maturity' of the community. Where there is already an established community, individual cells have to compete for resources and growth becomes strongly 'density-dependent' and doubling times become much longer. The minimum apparent doubling time for a diatom population in a study on the effect of current speed on communities from the R. Ithon was 14.4 days (14 °C; Antoine & Benson-Evans, 1982).

By contrast, rates of response of macrophytes to nutrient removal are slower. It took three years, for example, for *Ceratophyllum demersum* to recolonize Alderfen Broad subsequent to isolation from the R. Ant (Moss *et al.*, 1986). Recovery of the macrophytes of the R. Wear from pollution from deep coal mining was much slower (Holmes & Whitton, 1977; Birch *et al.*, 1989). Whilst macrophytes may represent good indicators of spatial differences in nutrients under relatively stable long-term conditions, their response to temporal change is more difficult to predict. Diatoms – and other algae – are more likely to respond to changes in nutrient concentrations within one or two months in scouring environments where 'internal loading' is unlikely to be a problem (Kelly & Whitton, 1995).

The TDI is deliberately simple and easy to use (see Appendix). Such an approach was also adopted for the earliest invertebrate indices in the U.K. (e.g. Woodiwiss, 1964). The widespread use of these as a result led not just to increasingly sophisticated indices (culminating in RIVPACS: Wright *et al.*, 1989), but also to a large body of expertise on the biology of benthic invertebrates that represents an extremely valuable basis for the interpretation of water quality. Use of TDI should lead to more refined diatom-based indices and to greater expertise within the NRA (and successor organisation) on which interpretations of nutrient status can be based.

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Appendix 1. Calculation of TDI is straightforward and can be readily automated using spreadsheet and database packages. An example (R. Browney, upstream of discharge, 5 July 1994) is presented below. Pollution-tolerant taxa are indicated by asteriks in the last column. Sensitivities (s) and indicator values (v) are listed in Table 4.

Taxon	Count (a)	s	v	asv	av	Tolerant
Cocconeis placentula	54	3	2	324	108	
Cocconeis pediculus	38	4	2	304	76	
Cyclotella meneghiniana	34	5	1	170	34	
Amphora pediculus	23	5	2	230	46	
Rhoicosphenia abbreviata	15	4	1	60	15	
Navicula lanceolata	11	5	2	110	22	*
Nitzschia inconspicua	10	4	1	40	10	*
Achnanthes minutissima	8	2	2	32	16	
Nitzschia dissipata	7	4	2	56	14	
Reimeria sinuata	7	4	3	84	21	
Navicula gregaria	5	5	1	25	5	*
Diatoma moniliformis	4	2	1	8	4	
Achnanthes lanceolata	4	5	2	40	8	
Gomphonema parvulum	4	5	3	60	12	*
Diatoma vulgare	3	5	3	45	9	
Navicula cryptotenella	2	5	2	20	4	
Cymbella silesiaca	1	3	2	6	3	
Ctenophora pulchella	1	3	2	6	3	
Ctenophora pulchella	1	2	1	2	1	
Gomphonema olivaceum	1	5	2	10	5	
Navicula minima	1	5	1	5	1	*
Navicula muralis	1	5	1	5	1	*
Navicula tripunctata	1	4	2	8	2	
Nitzschia amphibia	1	4	3	12	3	
Stauroneis alpina	1	5	2	10	2	
Total	237			1666	422	32

TDI = $\sum$asv/$\sum$sv = 1666/422 = 3.95
% pollution tolerant taxa = (32/237) × 100 = 13.5
Interpretation
The data indicate a fairly eutrophic site (TDI = 3.95) free from significant organic pollution (% pollution tolerant taxa < 20%; see Table 6).